Failure analyses on the Lint trains operated by Arriva Tog Danmark

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Summary

Arriva Tog Danmark operates six train lines in Central and West Jutland and serves approximately 6.5 million train passengers each year. Maintenance on the 43 Alstom Lint trains is mostly done by their own mechanics in the Arriva work shops in Varde and Struer. This gives a large amount of flexibility and opportunities to reduce maintenance costs, but of course brings along the responsibility of making sure the trains are maintained well and have as little failures as possible.

This report is the final product of my four-month during internship at Arriva Tog Danmark at the office in Varde. The internship consisted of two assignments regarding the failures of the Lint trains and are both included in this report. First the unplanned maintenance data was analysed. Besides giving Arriva Tog an insight in their unplanned maintenance tasks, this also resulted in recommendations about storing the failure data in the future. In the second assignment, a Failure Mode, Effects and Criticality Analysis (FMECA) with Maintenance Feedback Analysis (MFA) was done on the Power Pack of the Lint trains. These analyses gave opportunities for making changes to the maintenance planning and more recommendations about what kind of data and how failure data can be stored.

Contents

1 Introduction

For train operators performing the maintenance on their fleet themselves gives a lot of flexibility and opportunities to reduce maintenance costs. For this to be realized it is very important that the maintenance schedule is based on accurate data and that this data is used to optimize the maintenance planning.

Arriva Tog Danmark operates 43 trains, these trains operate 15% of the Danish rail and serve 6.5 million travelers every year. Arriva performs most of the maintenance on the trains in their own work shops in Varde and Struer. At the moment the maintenance schedule is being updated for the future and a new computer system is designed. To provide Arriva with insights in their failure data and making recommendations for storing failure data in the new system the failure notifications of the trains are analysed. Next a Failure Mode, Effects and Criticality Analysis (FMECA) with Maintenance Feedback Analysis (MFA) is done on the Power Pack of the Lint trains. This results in recommendations for the maintenance planning on this system and more recommendations about what and how data should be stored for future analyses.

2 Assignment 1: Analyses on the unplanned maintenance data

The first assignment consists of analyzing the unplanned maintenance tasks. For Arriva it is interesting and important to know for example which failures occur most frequently and if there are differences between the older and newer train sets. From these analyses recommendations about storing maintenance data in the new system and conclusions about the unplanned maintenance tasks will be given.

2.1 Method

The unplanned maintenance tasks/failure notifications are the tasks that the train drivers have submitted and that were assigned a work order by the daily planners. To analyse the unplanned maintenance, the data sheet with almost 1500 failure alerts (from 01-01-2016 to 31-12-2016) from the trains was categorized in the 11 categories of train parts, see appendix A. Then the most common failures were categorized within the 11 categories. Lastly, the data sheet with the actual maintenance planning in the workshops was compared to the failure reports to determine if a train had to be brought into the workshop especially to repair the reported error.
From the train number the batch number (1-3) and train type (Lint1 or Lint2) can be derived.
The complete data sheet consists of the following data:

- The date on which the failure alert was marked 'closed'
- The train number
- The category (1 of 11) to which the failed part belongs to, see appendix A
- The self-assigned part/failure type within the category
- If the train had to be brought into the workshop especially for the failure alert, binary
- The batch number
- The train type
- The down time
- The explanation of the failure (in Danish)

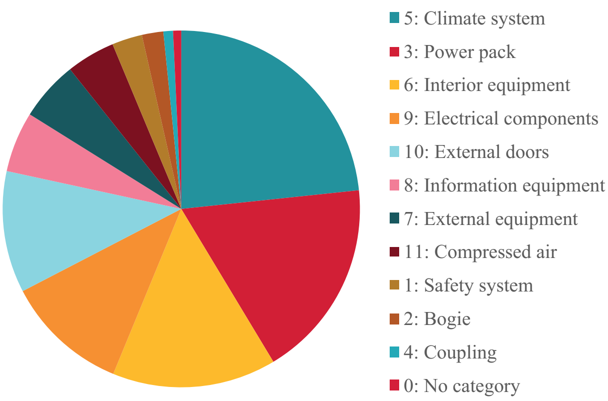


Figure 2.1: Number of notifications per category

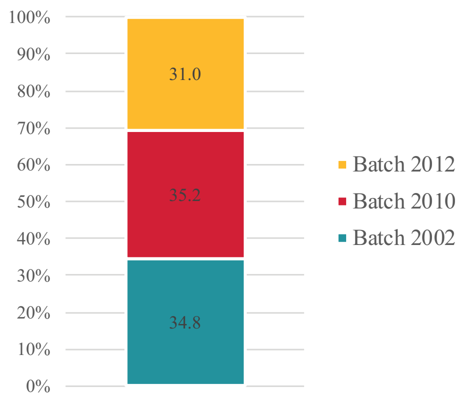


Figure 2.2: Number of notifications per train per year

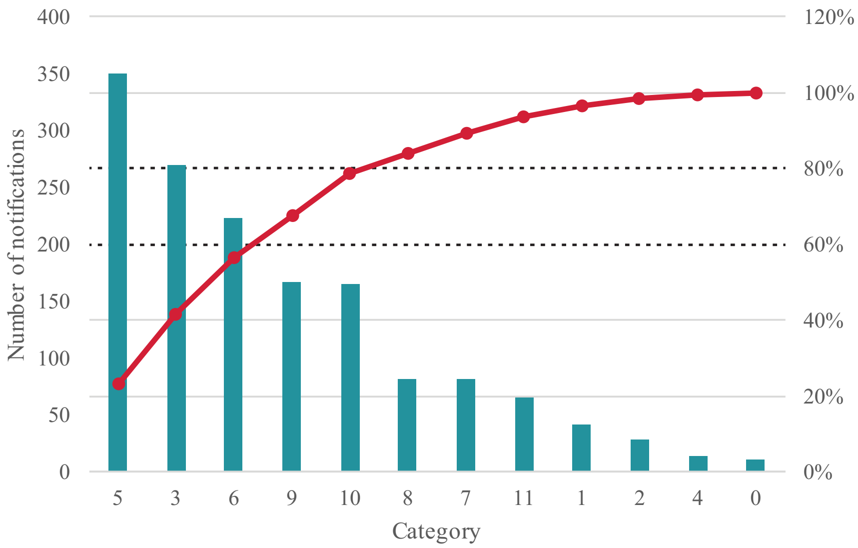


Figure 2.3: Pareto chart of the number of notifications

2.2 Results

First, some general numbers and graphs are shown to give an overview of the data. At the moment, Arriva has 43 trains in operation in Denmark. These trains went into operation in three batches: 29 trains of type Lint1 in 2002, 12 trains of type Lint2 in 2010 and 2 trains of type Lint2 in 2012.

In total the data sheet consists of 1496 failure notifications. These notifications are divided into 11 categories plus a category '0' meaning the notification could not be placed in one of the categories, for example because it concerns a failure that is not part of the train itself or the explanation was not clear about what had happened.
The notifications are divided as shown in figure 2.1. It is clear that Climate system (category 5), Power pack (category 3) and Interior equipment(category 6) make up more than half of all failure notifications. Figure 2.3 is a Pareto chart of the number of failure notifications in the different categories. Although the chart does not comply to the Pareto principle that 80% of the failures is caused by 20% of the causes, it does show that the first three categories cause almost 60% of all failures.

In figure 2.2 the number of notifications per train per year, divided into the three batches is shown. It can be seen that the trains from the the two first batches have more notifications than the trains from the last batch. But as mentioned, the batch from 2012 consists only of two trains, so this could be just a coincidence.
Table 2.1 shows the number of notifications per month. This shows that winter (January, February, November and December) and the beginning of summer (May and June) are the periods with the highest number of notifications in 2016. In figure 2.5 a boxplot of the data in table 2.1 shows the distribution of the number of notifications per month. The outlier is month 6, June, which clearly has more failure reports than the other months.
From table 2.1 and figure 2.4 it can be seen that from all the failure notifications that train drivers submit 50% is given a work order to be repaired. This shows that in June more than 60% of all notifications is given a work order to be repaired, which results in June being the outlier. However, that could be partly explained by the fact that in June less trains are in operation on a daily basis. This means that more trains are free to be taken in to repair and the daily maintenance planners tend to get trains in more frequently for repairs. The other notable month is September, in which only 38% of the failure notifications is given a work order. In figure 2.4 it is shown that September is a peak month and is the month in which the train drivers have submitted the most notifications in total. There are a number of reasons that could explain this, like the failure notifications being not such a pressing issue or too less time free on work shop tracks to repair the failures, but non of these reasons were examined in this assignment for being the underlying cause. Of course this could be a possibility for future analyses.

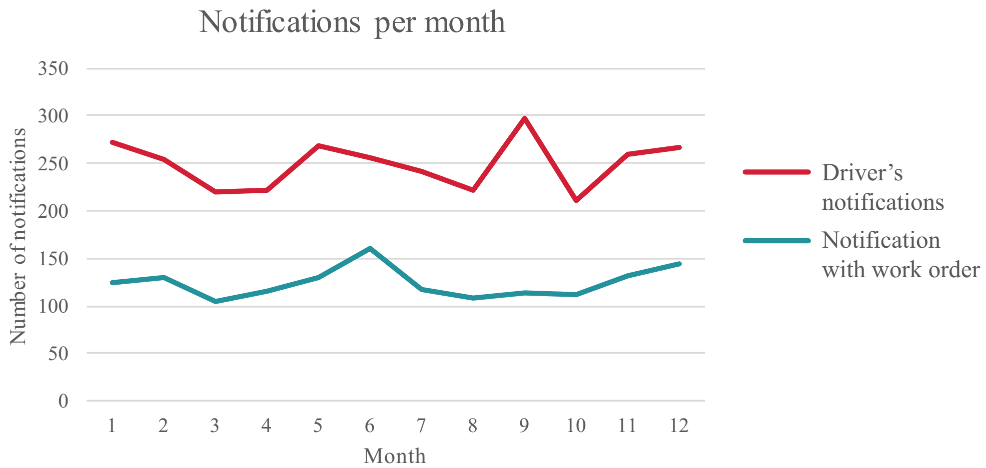


Figure 2.4: Number of all of drivers' notifications and the number of notifications of these that were assigned a work order number

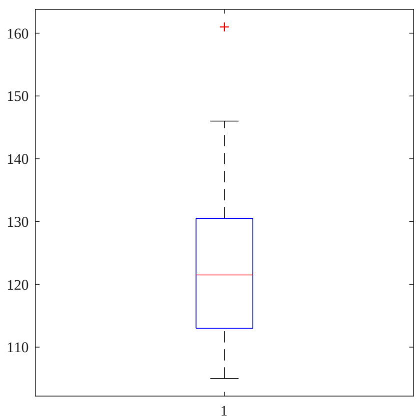


Figure 2.5: Boxplot of failures per month

Month	*work order notif.*	*total notif.*	*%*
1. January	125	272	46%
2. February	130	254	51%
3. March	105	219	48%
4. April	116	221	52%
5. May	129	268	48%
6. June	**161**	**255**	**63%**
7. July	118	242	49%
8. August	109	222	49%
9. September	**113**	**298**	**38%**
10. October	113	210	54%
11. November	131	260	50%
12. December	146	267	55%
Total	*1496*	*2988*	*50%*

Table 2.1: Number of failure notifications per month assigned a work order and the total of notifications and the percentage of notification which were assigned a work order, with outliers June(high) and September(low)

If we look at the categories within each month (figure 2.7) we can find out which kind of failures were dominant during the months with the most failure notifications. In the first two months of 2016, Climate system(5) makes up for a large part of all notifications. In the next few months these climate failures are decreased, with a minimum in month 5, May. In this month however, Power pack(3) failures have a large increase, which is also the case in month 6, June. In June the climate system failures also rise again. In July the same two categories ensure a decrease in the total amount of notifications. In the last two months of 2016, the number of notifications rises due to an increase in climate system failures and a higher amount of notifications in all of the smaller categories. Looking at the rest of the categories, it is obvious that Interior equipment(6) also has a significant share of the failure notifications each month. It could be stated that the categories 3, 5 and 6 are underlying in most changes in the failure notifications each month, which is a good reason to zoom in on these three categories.

In figure 2.8 the most common failures within the categories that were mentioned in the last paragraph (3, 5 and 6) are shown. Power pack (3) mainly consists of engine errors, generator errors and the category

'blank', which consists of all remaining failures. The rise we saw in May and June for this category seems to be caused by a large increase in engine and generator failures.
Climate system (5) has three failures that are very dominant: heating, cooling water leakage and the cooling water level being low. However, the latter two are related and could be grouped, which would result in this category having more than half of all failures. In this case we are left with only two failure types: coolant leakage and a heating error. The significant in- and decreases of the climate system failures are not caused by specific failures, both the coolant leakage and heating errors in- and decreases cause them.
Interior equipment (6) has two main failures next to the 'blank' failures: the toilet failures and the driver seat failures. The fact that the train drivers are the ones that submit the failure notifications might explain why the driver seat failures are noted this often.

Figure 2.6 shows the percentage distribution of the failure notifications between the two train types. The two differences that should be noted are in category 9: Electrical components and category 10: External doors. The train type Lint1 (relatively) has more Electrical component problems whereas train type Lint2 has more External door problems.

Figure 2.9a shows the number of notifications divided per month between failure notifications where the train was brought into the shop for this failure separately(yellow) and failures where this did not happen(red). The blue dots mark which percentage of all failure notifications was brought into the work shop separately. These percentages vary between 29% and 52%. January(50%) an February(52%) have the highest part of failures which were brought into the work shop separately. Failures that lead to trains having to be brought in can be called *critical* failures. Note that critical in this case doesn't (always) mean that the train could not function without repairs or that it may could harm the driver or passengers. It means that the Daily Planners found the failure notification critical enough to assign a work order and bring the train in just for this failure without regular (planned) maintenance being done on the train.
It could be stated that January and February had the largest amount of critical failures. July(29%) and September(31%) have the least amount of these critical failures.
Figure 2.9b shows the same comparison, but this time divided between the different categories. Focusing on the categories with more than 60 failure notifications in total, it is clear that half of the failures from categories Power pack (3), Climate system (5) and Exterior doors (10) are brought into the work shop separately. This means that of the two categories with most failure reports (3 and 5), half of all failures results in a train needing to be taken to the work shop an extra time. On the one hand this seems logical: the categories that include critical failures are the categories in which the most failures are reported. But on the other hand this implies that there is a lot of room for improvement in the scheduled maintenance to prevent failures from happening.

2.3 Conclusions

From the analyses of the failure notification data, a couple of conclusions can be drawn. Summarizing it is clear that the three categories with the most failure notifications are the Climate system(5), Power pack(3) and Interior equipment(6), which together make up for almost 60% of all failure notifications. From the specific failures within the categories it seems that the largest gain can be achieved by solving the cooling water leakage problem.
There is no hard evidence that there is a difference between the amount of failure reports of the older (batch 2002) and the newer (batch 2010,2012) trains.

I compared my conclusions from the data with some Arriva employees, to see if assumptions based on experience about the train's failures would match the data. We agreed about the climate system and power pack being the most common notified failures in the trains. The interior equipment at number three is somewhat less expected, but can be explained by the fact that the train drivers seem to report their driver seat being broken very often and because a broken toilet gives a lot of inconvenience like a bad smell, so this will be reported often. We agreed about the fact that the main problem in the trains is the cooling water leakage, which leads to a low water level in the trains. This is a problem that Arriva examined and are trying to fix by changing all of the climate system hoses' connections.
One thing that was surprising for the team was the fact that the doors of the Lint2 train seem to fail more often than those of the Lint1 train. The team had been talking about overhauling the doors of the

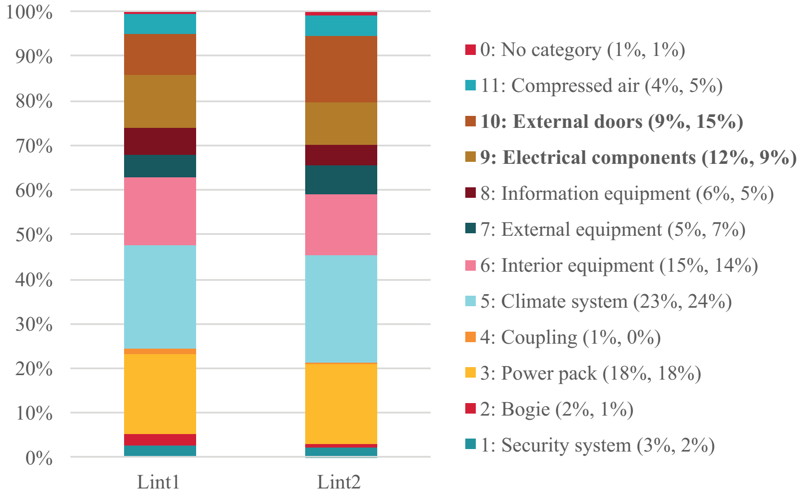


Figure 2.6: Percentage breakdown of failure notifications for Lint1 and Lint2 trains

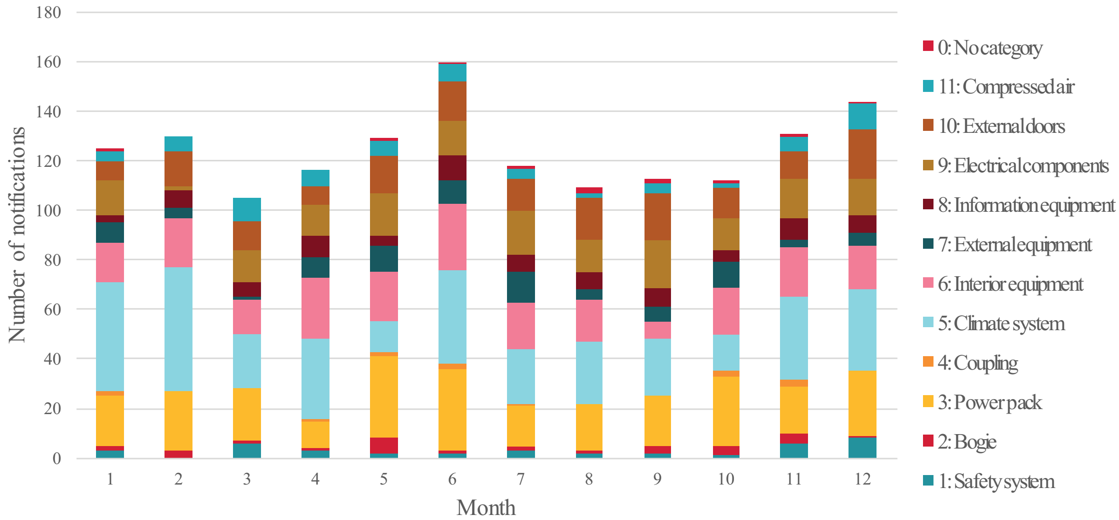


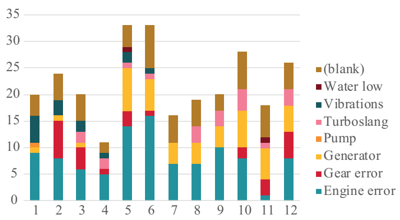
Figure 2.7: Notifications per month per category

Lint1 train because they had the idea that those doors failed more often. However, the data suggests the opposite and would suggest the doors of the Lint2 train should (also) be overhauled.

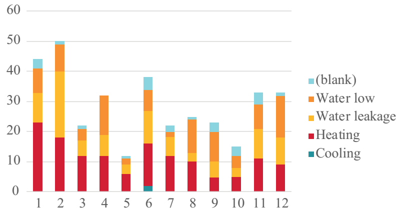
To create a convenient overview, all recommendations resulting from the assignments are grouped in chapter 4.

Discussion

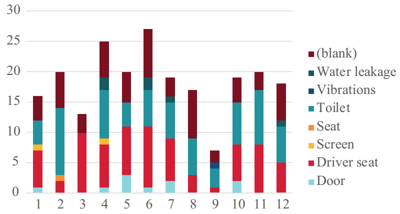
It must be noted that Arriva uses multiple ways of storing and using their failure and maintenance data. Some failures are reported in a different system and are repaired on the tracks, in which case the failure is not present in my data. Also, not everything that is being repaired in the shops is mentioned in the planning sheets, because they are supposed to be concise and to the point. This means I do not have the most accurate data set possible, but this has been a trade-off between the amount of work spend on completing a data set and whether it is an accurate reflection of the truth. I believe for the way the failure data is stored at the moment I worked with a data set that could bring an accurate enough insight in the failure behavior of the trains.



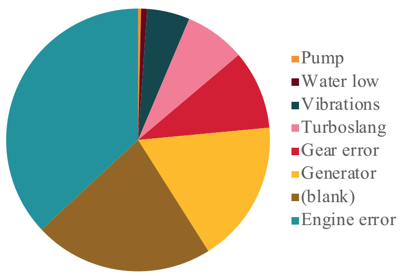
(a) Failures in category 3: Power pack



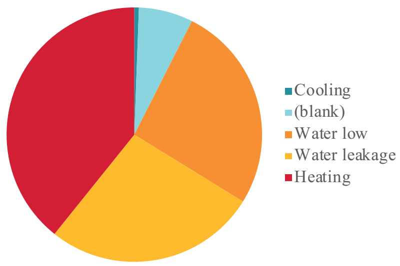
(b) Failures in category 5: Climate system



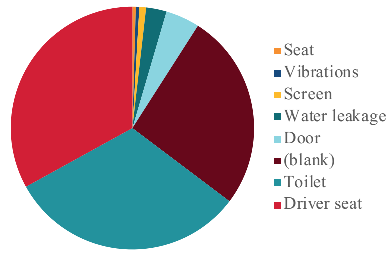
(c) Failures in category 6: Interior equipment



(d) Failures in category 3: Power pack

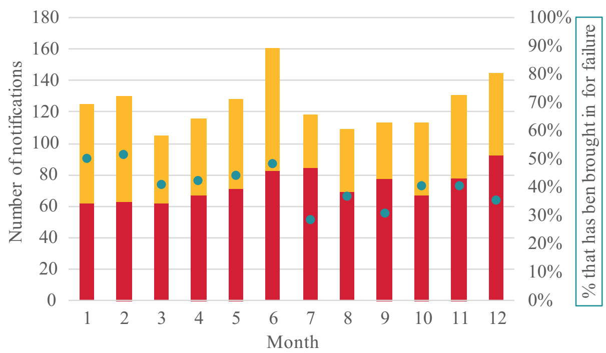


(e) Failures in category 5: Climate system

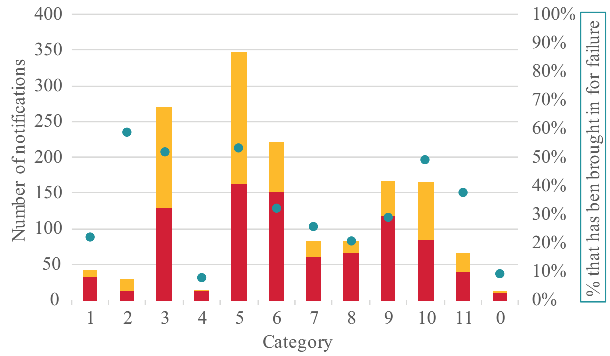


(f) Failures in category 6: Interior equipment

Figure 2.8: Failure notifications of categories 3, 5 and 6. These categories are the ones which make up for most of the failure notifications.



(a) Divided per month



(b) Divided per category

Figure 2.9: Yellow: critical failure notifications (failure notifications with a work order that have lead to a train being brought into the work shop) and red: non-critical failure notifications with a work order. Blue: the percentage of critical failure notifications.

3 Assignment 2: Failure Mode and Effect Analysis of the Power pack Lint1

In the second assignment a Failure Mode, Effects and Criticality Analysis (FMECA) of the Power pack will be done. An FMECA consists of all possible failures of a system and all effects of these failures. This method was first described in 1949 by the US Armed Forces Military to analyse risks and problems arising in military systems. NASA later used it for their aerospace systems to minimize risks because of few previous examples in this industry. Later it was adopted by the automotive industry and now many standards and adaptations are widely used in all kinds of industries.(Carlson, 2014; Braaksma, 2012)

3.1 Method

The FMECA analysis is an important part of the Reliability Centered Maintenance (RCM) methodology. Figure 3.1 shows the steps of the RCM method with the FMEA incorporated. The first five steps together are the FMECA and is performed by filling out the columns of figure 3.2, which is the FMECA table used in this assignment. This sheet is adapted from different sheets found in literature.(NASA, 2008; Braaksma, 2012)

Step 1: Identify System

Step 1 of the RCM methodology and the FMEA is identifying the system or equipment to analyse. This means choosing which parts and systems will be analysed, setting the boundaries of the analysis and to what extent the analysis will be carried out. In this case an intuitive RCM approach is suitable, because there is already a lot of knowledge of the systems functions and failures. An intuitive RCM approach means not all parts and failure modes are taken into account and the analysis does not include failure modes that never occur or are not critical at all to the system.

In this case we decided to choose the Power Pack for the analysis. This system is divided in four subsystems: Engine, Gear Box, Generator and the Hydraulic System. The parts within these subsystems that are included are chosen by examining the maintenance tasks in the current planning and the documentation of the external companies that do the overhaul of the Power Pack.

Step 2: Determine functions

Step 2 is very straight forward: determining the functions of the parts or assemblies of the system. The functions were described using mostly Wikipedia and help from the engineers in the workshop.

Step 3 and 4: Describing failures and failure modes

The third and fourth step of the FMEA are describing the functional failures and failure modes. Functional failures are the failing of the functions determined in step 3. The failure modes are the ways in which the part fails to perform its function. An example taken from (Picknell, 1999): A cylinder may be stuck in one position because of a lack of lubrication by the hydraulic fluid. The functional failure is the failure to stroke or provide linear motions, but the failure mode is the loss of lubricant properties of the hydraulic fluid.

Step 5: Identify consequences of failures

The consequences of the failures are described in terms of effect on safety of the system, health of the personnel and passengers and negative effects on the environment. This determines the criticality of a failure and gives the opportunity to decide if and what kind of action must be taken to reduce the likelihood of this failure happening.(Picknell, 1999)

Failure Mode, Effects and Criticality Analysis (FMECA)

An FMEA is a purely qualitative analysis, only including possible failures and effects. A way of making it a more quantitative analysis is by adding a criticality analysis. This means every failure mode is assigned a specific criticality by grading it a Risk Priority Number (RPN). This RPN is a multiplication of the Severity, Occurrence and Detection ratings. These three parameters are generally assigned a value by using tables with a scale. In this assignment adaptions of tables found in different literature are used,

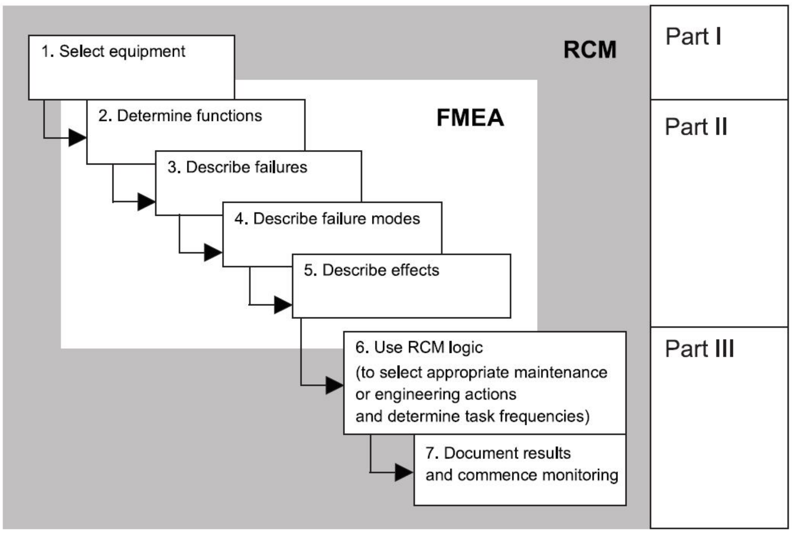


Figure 3.1: Steps in the RCM method (Braaksma, 2012)

which are shown in tables B.1 to B.3 in appendix B.(NASA, 2008; Tinga, 2012)

Step 6: Use RCM logic
Step 6 in figure 3.1 is using the RCM logic. This means that the appropriate action for a failure mode is selected. The ideal result of selecting the action is eliminating the failure mode. If that is not possible the risk of failure should be reduced. Often the easiest way is to increase the probability of detection of the failure. However, this can be expensive and it does not improve the system quality-wise. Reducing the occurrence of the failure mode is thus a better goal.

There are several logic trees to select the appropriate action for a failure mode. In this case we use the NASA RCM Logic Tree taken from (NASA, 2008), see figure B.1. In this logic tree there are four possible outcomes: Performing a Predictive Testing and Inspection(PT&I) task, Performing an interval based task, Redesigning or accepting the risk and Run-to-Fail.
PT&I technologies are used to assess the condition of the systems and parts and let the user determine an appropriate maintenance action or interval. Some examples of PT&I technologies are Vibration Monitoring, Infrared Thermography and Ultrasonic Noise Detection. In this case these more progressive PT&I techniques will probably not be a suitable solution, because of a lack of the necessary equipment in the work shops for these kind of tasks.
Developing and scheduling an interval based task can be done in for example time or cycle based intervals. In this case, most parts are already checked on a kilometer-based interval. If the RCM logic results in the interval-based option, this will mean that it is proposed to re-address the interval that it is checked now. When there is no option for a maintenance action to reduce the risk of failure, redesigning can be an option. However, in this case, where the system is already designed and in operation for a long time, this will not be an obvious choice for most failure modes. This means that this RCM logic tree result means that the maintenance action that is taken now is proposed to be re-addressed. This can result in using different maintenance actions or for example different materials/spare parts to fix the failure.
Run-to-Fail is the easiest approach: You do not perform any action and wait until the failure has happened to repair.

At the moment Arriva is in the end-phase changing their maintenance planning to merge the previously separate schedules for the Lint1 and Lint2 trains with inconvenient intervals. There used to be 5 kilometer-based intervals, with an increasing number of tasks to be done at each interval. These intervals were structured so that after every $x_1$km task package 1 must be carried out. Every $x_2$km, package 2 must be carried out, etc. In which $x_1 < x_2 < x_3 < x_4 < x_5$. This often was a cause for planning issues during the task package 4 and 5, because of the large amount of tasks in those packages. This also meant that tasks that would ideally have to be done in between two intervals would always be done at the shorter

System	Subsystem	Function	Failure mode	Effect of failure	SEV	OCC	DET	RPN	Potential causes	Current detection method	Type of action	Recommended action

Figure 3.2: FMECA table

interval period, which means that is actually done too often. Arriva is changing this to a schedule with 24 evenly spread fixed intervals of 25000 kilometers, so all tasks can be planned when necessary. At the and of the FMECA the recommended actions will be compared to the new maintenance schedule as proposed by Arriva.

3.1.1 Maintenance Feedback Analysis

Doing an FMECA and using the results for changing the maintenance plan should ideally be done as early as possible and it should be continuously updated with new data, making it a 'living' program. This means new failure modes and new information about for example the occurrence of failures need to be used to update the FMECA. For this, a Maintenance Feedback Analysis (MFA) can be conducted. The method proposed in (Braaksma, 2012) is adopted in this assignment. The steps of this MFA are done between step 6 and 7 of figure 3.1.

Step 1: Determining if Maintenance Feedback is worthwhile
This first step gives insight in if it is worthwhile to try to reduce uncertainties in the FMECA. You describe the most important assumptions and uncertainties in the data that is the basis of the FMECA and you determine if there is a potential for improvement of these uncertainties. This thus gives you the uncertainties and their causes and improvement potential.

Step 2: Determining data analysis requirements for feedback
When the previous step outcomes suggest there is potential for improvement, this step will result in the preferred data analysis and the data requirements. For this you choose if in the future qualitative (experience-based) and/or quantitative analysis should be done and determine the data requirements for this kind of analysis.

Step 3: Organizing data collection
Determine what kind of data and how the data is already monitored and stored. This gives an insight in how to change this in order to make sure all needed data is collected. Normally, in this step a cost-benefit analysis will be done to see if the proposed data collection is worthwhile. If not, changes in the kind of analysis or data collection must be made.
With the required data being collected, once in a while the chosen analyses should be carried out and the results used for updating the RCM/FMECA outcomes and eventually your maintenance planning.

Input for the FMECA table
I made a set-up for the FMECA table with all parts, functions, failure modes and effects. Then I explained the scheme to the workshop manager and asked him to help me make the adjustments and corrections to my content. He also rated the Severity, Occurrence and Detection scores. After this, mechanics in the workshop that are experts on the Power Pack scored the S, O and D rating too. The final rating is the average of these scores.

3.2 Results

Failure Mode, Effect and Criticality Analysis

When the Risk Priority Numbers (RPN) are assigned, decisions about future actions can be made with help of the RCM logic (tree). The four options are performing an PT&I task, change the interval of the task, redesign/change the maintenance actions or accepting the risk and Run-to-Fail.
For failure modes with a low RPN ($\leq$81) it is decided that the current maintenance set-up is sufficient and no changes have to me made. Risk priority numbers are specific for an FMECA. Therefore, the thresholds mentioned in this report are derived from the RPN scale in this FMECA. In figure B.1 this means the route is **Yes**: There is an adverse effect→**No**: There is no (cost-)effective PT&I approach→**No**: There is

no (cost-)effective (change) in interval, ending up at Redesign or accept the risk, in which we choose the latter one. For these failure modes it could also be considered to increase the amount of kilometers at which there is a check or maintenance.
RPNs between 100 and 200 mostly result in a proposal to make a change in the maintenance set-up. In this case the most chosen action is to address the interval of certain checks. In the logic tree this means that the route taken is **Yes→No→Yes**: There is a (cost-)effective (change) in interval. This can be the visual check or if necessary a more specific check of for example the grease or oil in a bearing.
The differences in RPNs is mostly due to differences in the Occurrence score. The failure modes with the highest RPNs (≥200) are thus the ones which occur very frequently. This can mean that the parts are not checked or maintained often enough, in which an increase in the amount of checks could be done. It can also mean that an overhaul or a change in maintenance action done or material or spare parts used could be cost-efficient.

Maintenance Feedback Analysis

The first step of the MFA is to describe the most important assumptions and uncertainties and determine if Maintenance Feedback is worthwhile. In this case the most important uncertainties are the lack of technical in-depth knowledge on my side of the system. To make sure that all colleagues I would ask for their input would have to invest minimal time, I made a set-up of the filled FMEA table and asked colleagues for their input and comments. This means that people may overlook missing parts, functions or failure modes more easily than when the FMEA table would be filled out by experts in the first place. Also, although my colleagues speak English well, the fact that English is the second language for both of us can have an effect on the understanding about what I was asking of my colleagues and the way I interpret the comments of my colleagues.
In this FMECA, no real quantitative data is used, because data was not stored in a structural way before. All information and knowledge used in this FMECA is based on expert knowledge and can thus deviate from the truth.
Lastly, the background of all contributors is quite similar, it would be good to have a more mixed pool of contributors to make sure different points of view have had a chance to look at the FMECA.
The uncertainties that are describes above are all things that can be reduced fairly easily by a more structured data collection and by forming a team with people with different backgrounds.

In step two the needed analyses are determined. Taking into account the results of the first assignment about the unplanned maintenance, I think that quantitative analyses would be a great way of getting more insight in the failures that occur and the maintenance that is done right now. If this is clear, the FMECA can be updated to see if there are options for changes in the maintenance planning to make it more (cost-)efficient. The data requirements for these kind of quantitative analyses are that all failure modes are stored. Also the way the failure mode is detected and fixed need to be clear.

Step three consists of determining the actions needed for the data collection of step two. This is in line with the recommendations that followed from assignment 1. One of the conclusions of the first assignment was that data collection should be improved. Briefly, the recommendations are to make sure failures are registered uniformly, separately and in a standardized way. In section 4.1 the recommendations regarding storing data following from assignment 1 and 2 are combined. In section 4.3 a workflow is proposed for storing failure data. This workflow is based on the event of a failure that is discovered while driving. Of course, failure data of problems discovered during planned maintenance should be stored in the system in the same way.

4 Recommendations

4.1 Assignment 1: Recommendations following from the analyses and possible future analyses

In the following chapter, some possible actions following from the analyses in the first assignment some future analyses are recommended.

Recommended actions

First, I would recommend to structure the SAP system in a way that makes it easy to extract reliable data. The 11 categories with parts specified within the categories are very convenient for this because it is easy, intuitive and fast for mechanics and daily planners to store data. More specific ideas on this topic can be found in section 4.3.
Secondly, I would recommend to closely monitor the failures of cooling liquid leakage (cat. 5) and the engine errors (cat. 3). Asking mechanics to specify the cause and the used solution in these failures will help by making decisions about the maintenance and to verify if the now used solutions are effective. This ultimately will decrease the failures of categories 5 and 3, which now make up for more than 40% of all failure notifications.
At the moment Arriva Tog Denmark is thinking of overhauling the doors of the Lint1 trains. On this topic I would recommend to overhaul the exterior doors of one Lint1 train and one Lint2 train. The specific trains I would recommend are 1024 and 2049, because those trains have the largest amount of exterior door failure notifications. This probably will give insight in the failure modes of the doors, which can be the basis of a (perhaps FMEA-based) change in the maintenance actions and maintenance planning for the exterior doors to reduce failures.
During the processing of the data it appeared that some drivers try to fix the problem by resetting systems, while others (seem to) just report the failure. It might have a positive effect on the amount of failures if all train drivers have sufficient knowledge about resetting main (electrical) systems like the heating, the engine/generator and the exterior doors.

Analyses

When the failure and maintenance data is stored systematically in the system, a lot of new possibilities for analyzing the data arise. First of all, it will give a clear insight in the kind and amount of failures that occur in the trains. This way individual trains, but also (parts of) the whole fleet can be monitored and well-founded choices about changes in maintenance intervals or materials used can be made. Some interesting features that might follow from the data are highlighted below.
When mechanics enter the time they've spent on a repair, over time the system will be able to give a more accurate indication of the expected repair time and the planning of the mechanics and the trains in the work shop can be made more accurate and thus more efficient.
It can also be interesting to see how much the tracks in the workshop are occupied by failed trains and how much by trains that are in for scheduled maintenance. When Arriva wins the contracts in 2017, the fleet will most likely need to increase and with that, the workshop space might too. For a good indication of how much the workshops might have to increase, it is important to know how often and how long tracks are normally occupied for both the scheduled maintenance and the unplanned repair tasks. With this, it is easier to decide where new workshop space needs to be build, at which workshop which kind of maintenance is done and where to stock which spare parts.
It could be very interesting to see which categories are the most 'expensive'. For this the amount of hours worked on repairs and replacements, so the man hour costs, and the costs of used spare parts must be added. This gives an insight in where Arriva could try to reduce costs in maintenance. This can also give an insight in which parts that are now repaired could better just be replaced or vice versa.

Registering failures and maintenance tasks in SAP

To be able to analyse the (planned and unplanned) maintenance tasks in the future, it is vital that the data is registered in a clear and uniform way. A couple of suggestions to do this are elaborated on in the following section. Furthermore, a workflow in how the failure data could be saved is proposed in section 4.3.

- **Make sure failures are registered in a uniform way**
  At the moment train drivers and daily planners type their own description of the failure. This results in a lot of different descriptions of the same problem and no way of getting a quick overview of the failure data. Registering failures in a uniform way could be done by making the user choose from drop-down menus. This way Daily Planners and Mechanics are forced to uniformly store data. An open field for comments gives the user the possibility to elaborate on their observations. This also gives the opportunity for the system to provide support to the mechanic: If the failure is categorized the system can give options for the spare parts or tools that are associated with a specific failure or the system can show if the same train has had similar problems in the past.

- **Make sure every failure is registered separately**
  Users sometimes register more than one failure of a train in one task. To be able to easily analyse the failure data it is important that every failure is registered on their own. If there is more than one failure on a train, they should be reported separately. Although this is a small increase in workload for the employees, data about the failures can be analysed much more easily, without having to manually separate tasks later.

- **Add more data**
  For an analysis, more data usually means more options to analyse. For the purpose of analyzing the failures and (unplanned) maintenance tasks, one could think of interesting characteristics to add to the database. Some examples are:

  - The **date** at which the error was **reported**.
  - The actual **date** of the **repair**. This could have been deduced from the maintenance planning, but it would be convenient if all the data would be in one place.
    The two dates mentioned above, could also easily give the **amount of time between** the **notification** and the **repair**.
  - If the train is **brought into the workshop an extra time**, especially for this failure, to be repaired (Unplanned maintenance, binary)
  - The **failure mode**. This can be another drop-down menu in which the user can choose from the most common failure modes.
  - The **time** and/or **amount of kilometers** driven since the last planned inspection of the train.

    Together with the previously mentioned data (see below), this would complete a data-set with a lot of usable data for analyses.
  - The **train number**
  - The **category (1 of 11)** to which the failed part belongs to
  - The **part** within the category
  - The **age** of the train (which batch the train belongs to)
  - The comments on the failure

4.2 Assignment 2: Recommendations following from FMECA with MFA

Failure Mode, Effects and Criticality Analysis

As mentioned in the results in section 3.2, there are three main recommendations from the FMECA. First it is recommended that for almost half of the failure modes included there is no change necessary in the maintenance planning. However, the intervals of the checks on these failure modes might be reevaluated to decrease the amount of checks.
The next category of recommendations is to address the interval of the amount of checks, ensuring that the state of the parts are monitored at the right interval to be able to perform maintenance on the right moment, before the failure actually occurs.
The last recommendation is for the failure modes of the gearbox and generator. The RPN is high and this can be a reason to evaluate if these parts are up for an overhaul or replacement, so the failures will

occur less in the future.

The recommended actions from the FMECA (see appendix C) are compared to the changes as proposed by Arriva on their maintenance planning. In the maintenance planning parts like air, oil and fuel filters are replaced based on intervals and thus on amount of kilometers driven. The filters are also checked based on a shorter interval period. It could be cost-efficient to eliminate the interval-based replacements and only replace the filters when a check indicates it is necessary. The same goes for driving belts, which are also replaced on certain intervals. This also prevents that filters or driving belts that were just replaced due to a failure are replaced again because the interval in the maintenance planning states it is supposed to be replaced.
For a lot of the engine parts it was proposed to make no change in the maintenance planning or even to reduce the amount of checks. In the maintenance planning there is a separate task 'Checking engine for abnormal noise or vibrations, which is carried out every planned interval(25000 km). This seems like a good solution to not having to check every single part on certain intervals, but only when this general check indicates problems.

Maintenance Feedback Analysis

The first recommendation from the MFA is that when the FMECA is updated, this is done by a broad multidisciplinary team. This means a team with for example maintenance planners, workshop managers, warehouse manager and mechanics. Every employee has his own knowledge and view on which problems are most pressing. This results in a well-discussed and thus a well thought through analysis.

From the MFA it is clear that structured data collection is important for the feedback cycle and thus for improving the maintenance plan. Important characteristics of storing data were already discussed in the recommendations following from assignment 1. A possible workflow for storing the failure data for errors occurring during operation is given in section 4.3, which is based on both assignment 1 and 2. The most important contribution from assignment 2 is about storing failure modes. For the FMECA it is important that besides the functional failure the failure modes are registered, because this way quantitative data about the occurrence of the failure modes is stored. This can be done with a drop-down menu for the mechanic with different general failure modes.

4.3 Workflow storing failure data

Failure on track: train can not continue

1. Driver calls Daily Planners
2. Daily Planners make a work order with
   - *train number* (numbers)
   - *train side A-B* (drop-down)
   - *part category 1-11* (drop-down)

   and checks the box *'Down on track'*
3. Mechanic goes to the train and completes work order and adds
   - *part within category* (drop-down)
   - *failure mode* (drop-down)

   If the train is fixed:
4. Mechanic adds
   - *time spent on repair* (numbers)
5. Daily Planners check if everything is filled out and mark the work order as *'Done'*

   If the train is not fixed an brought into the work shop:
4. Daily Planners *'Check in'* the train on a *track number* and if applicable checks the box *'Only for failure'*
5. Mechanic completes work order and adds
   - *time spent on repair* (numbers)
6. Daily Planners check if everything is filled out and mark the work order as *'Done'*

Failure on track: train can continue

1. Driver makes notification of failure in SAP with
   - *train number* (numbers)
   - *train side A-B* (drop-down)
   - *part category 1-11* (drop-down)
2. Daily Planner makes failure into a work order

   When train is brought in the work shop
3. Daily Planners *'Check in'* the train on a *track number* and if applicable checks the box *'Only for failure'*
4. Mechanic completes work order and adds
   - *part within category* (drop-down)
   - *failure mode* (drop-down)
   - *time spent on repair* (numbers)
5. Daily Planners check if everything is filled out and mark the work order as *'Done'*

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Appendix A

Categories of train parts used by Arriva Tog, Varde

Category	*Short description*	*# of parts specified in A and B part of the train combined*
1. Safety system	Main computers, antennas and other equipment used for the safety signals	20
2. Bogie	Carriage of the train with wheels, axles and brakes included	40
3. Power Pack	Engines and gearbox	20
4. Coupling	Couplings between A and B part and between different train sets	5
5. Climate system	Pumps, valves, pipes and heating elements	26
6. Interior equipment	Seats, floors, interior doors, the toilet and all pictograms	14
7. External equipment	Windows, fuel tank and other external train parts	17
8. Information equipment	Passenger count system, internet, info displays and announcement system	13
9. Electrical components	Computers, wires, switches, power supplies and voltage inverter	14
10. External doors	Door panels, windows, engines and controls	16
11. Compressed air and brake system	Brake system, horn and valve controls	9

Appendix B

FMECA Logic Tree and Rating tables

Figure B.1: NASA Logic tree, no adjustments, from (NASA, 2008).

Tables B.1 to B.3: Severity Rating, adapted from (Reliasoft, 2015; NASA, 2008; Warwick Manufacturing Group, 2007) to suit this assignment.

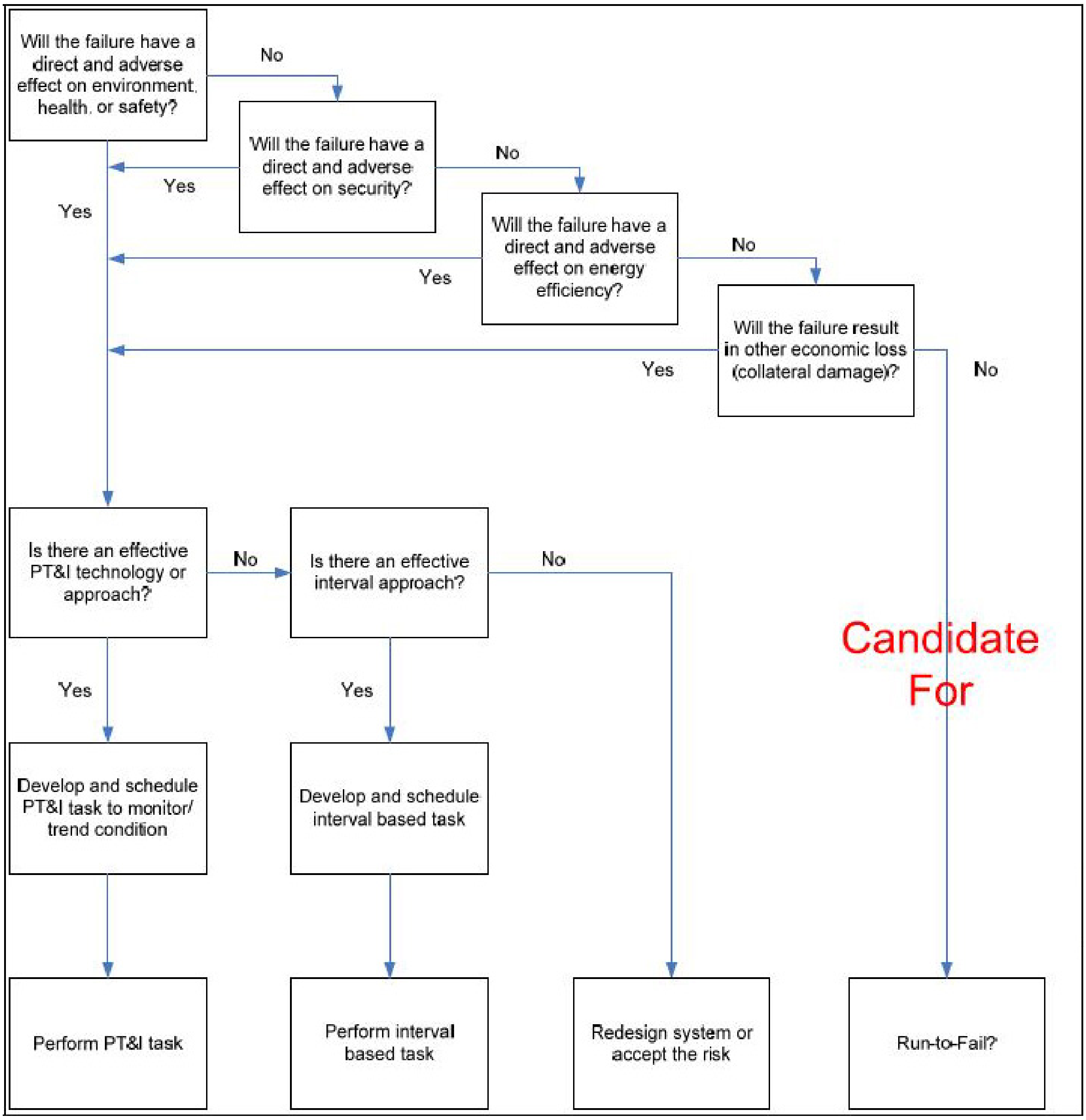

Figure B.1: NASA RCM Logic Tree (NASA, 2008)

#	*Description*	*Criteria 1*	*Criteria 2*
1	No effect	No discernible effect	No discernible effect
2	Annoyance	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by discriminating passenger/mechanic (<25%)	Slight inconvenience to process, operation or operator. Repair could be done by train operator without trouble call
3	Annoyance	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by discriminating passenger/mechanic (50%)	Slight inconvenience to process, operation or operator. Repair could be done by train operator during trouble call
4	Annoyance	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by discriminating passenger/mechanic (>75%)	Slight inconvenience to process, operation or operator. Repair can be done by mechanic very easily during planned maintenance, no delay
5	Degradation of Secondary Function	Degradation of secondary function (vehicle operable, but comfort/convenience functions at reduced level of performance)	Repair can be done during planned maintenance. Slight delay in repairing function
6	Loss of Secondary Function	Loss of secondary function (vehicle operable, but comfort/convenience functions inoperable)	Repair can be done during planned maintenance. Moderate delay in repairing function
7	Degradation of Primary Function	Degradation of primary function (vehicle operable, but at reduced level of performance)	Repair needs to be done outside of planned maintenance by own mechanics. Significant delay in repairing function
8	Loss of Primary Function	Loss of primary function (vehicle inoperable, does not affect safe vehicle operation)	Repair needs to be done outside of planned maintenance by external party. Significant delay in repairing function
9	Failure to Meet Safety and/or Regulatory	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning	May endanger passenger, environment or operator (machine or assembly) with warning
10	Failure to Meet Safety and/or Regulatory	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning	May endanger passenger, environment or operator (machine or assembly) without warning

Table B.1: Severity rating

#	*Description*	*Criteria*
1	Almost Certain	Failure is visually very obvious and always detected
2	Very High	Failure is visually obvious and very likely to be detected
3	High	Failure is easily detected when train gives specific signal
4	Moderately High	Failure is detected when train less specific gives signal
5	Moderate	Failure is very likely to be detected after manually/tactile checking
6	Low	Failure is likely to be detected after manually/tactile checking
7	Very Low	Failure is not likely to be detected after manually/tactile checking
8	Remote	Failure is not likely to be detected at any stage
9	Very Remote	Failure is not likely to be detected at any stage
10	Almost Impossible	There is no detection opportunity

Table B.2: Detection Rating

#	*Description*	*Criteria*
1	Very Low	Virtually never
2	Low	Less than once a year
3	Low	Once a year
4	Moderate	More than once a year
5	Moderate	Once every six months
6	Moderate	More than once every six months
7	High	Once a month
8	High	More than once a month
9	High	Once a week
10	Very High	More than once a week

Table B.3: Occurence Rating

Appendix C

FMECA table

System	Subsystem	Function	Failure mode	Effect of failure	SEV	OCC	DET	RPN	Potential causes	Current detection method	Recommended action
Engine	Fuel lines	Transport fuel	Crack in rubber or metal	Leakage of fuel	10	4	4	160	Wear of material	Leaked fuel, engine error	Adress visual check interval
	Vibration dampers	Damp vibrations		Vibrations and noise and damage to other parts	8	1	3	24		Vibrations --> Visual	No change of action
	Flywheel	Store rotational energy	Cracked or warped		8	1	3	24	Vibrations	Visual	No change of action
	Rocker arms	Convey movement from pushrod into movement of valves	Cracked or broken	Engine does not run	9	3	3	81	Static overload or fatigue	Engine error --> Visual	No change of action
	Pushrods	Convey motion from camshaft to rocker arm	Deformed or cracked	Engine does not run	9	3	3	81	Static overload or fatigue	Engine error --> Visual	No change of action
	Engine block	Housing of cylinders and other parts	Cracked	Engine does not run	9	3	3	81	Overheating	Engine error --> Visual	No change of action
	Crankshaft	Conversion between reciprocating (of piston) motion and rotational motion	Misaligned	Engine does not run	9	3	3	81	Vibration, adjecent parts broken	Engine error --> Visual	No change of action
			Bent or cracked	Engine does not run	9	3	3	81	Vibration, fatigue	Engine error --> Visual	No change of action
	Camshaft	Operate valves	Wear		9	3	3	81	Wear, adjecent parts broken	Engine error --> Visual	No change of action
			Cracked		9	3	3	81	Wear, adjecent parts broken	Engine error --> Visual	No change of action
	Oil sump	Hold oil	Cracked or a hole	Oil leakage	9	6	3	162	Wear, external impact, corrosion	Leaked oil	Adress visual check interval
			Deteriorated rubber oil sump gasket	Oil leakage	9	6	3	162	Wear	Leaked oil	Adress visual check interval
	Connecting rods	Transfer motion from piston to the crankshaft	Deformed or cracked	Engine does not run	8	3	3	72	Static overload or fatigue	Engine error --> Visual	No change of action

	Fuel filters	Filter impurities from fuel	Clogged	Not enough fuel comes through, engine stops	8	4	4	128	Pollution	Visual	Adress visual check interval
	Air filters	Filter impurities from air	Clogged	Not enough aircomes through, engine runs	8	4	4	128	Pollution	Engine error --> Visual	Adress visual check interval
	Driving belts	Convey motion of different shafts	Cracked	Engine overheating	8	4	4	128	Wear	Computer alert	Adress visual check interval
	Fuel pump	Pump fuel from tank to engine	Wear	Engine does not run smoothly	8	4	4	128	Wear	Engine error	Adress visual check interval
	Turbocharger	Compress air to flow to engine	Worn or damaged wheels	Engine does not run smoothly	8	5	4	160	Pollution, foreign object, overheating	Engine error --> Visual	No change of action
	Bearings	Support shafts and reduce friction	Loss of lubrication	Engine does not run smoothly, if not adressed, serious damage to connecting parts	8	5	4	160	Insufficient or polluted oil/grease	Visual, oil/grease check	Adress interval visual check and grease/oil check
			Wear	Engine does not run smoothly, if not adressed, serious damage to connecting parts	8	5	4	160	Insufficient lubrication, overheating	Visual	Adress interval visual check and grease/oil check
	Cylinderhead	Housing of valves and fuel injector and passages for the fuel/air mixture	Cracked		8	1	4	32	Overheating	Visual	No change of action
	Water cooler	Remove waste heat from engine		Overheating	8	5	4	160		Computer alert	
Gearbox	Shafts	Carry the gears	Deformed or cracked	Not able to shift gears	8	7	4	224	Static overload or fatigue	Visual	Adress is overhaul is neccesary/cost-efficient
	Gears	Transmit power between shafts	Wear	No smooth gear shift	8	1	4	32	Wear	No smooth shit --> Visual	No change of action
			Teeth breakage	No smooth gear shift	8	1	4	32	Static overload or fatigue	No smooth shit --> Visual	No change of action

	Bearings	Support shafts and reduce friction	Loss of lubrication	No smooth gear shift, if not adressed, serious damage to connecting parts	8	7	4	224	Insufficient or polluted oil/grease	Visual	Adress interval visual check and grease/oil check
Generator		Convert mechanical energy to electrical energy	Not able to generate electrical energy (failure mode not specified)	Not able to generate electrical energy (failure mode not specified)	8	7	3	168			Adress is overhaul is neccesary/cost-efficient
Hydraulics	Pump	Convert a mechanical force into hydraulic fluid power. Transfer pressurized hydraulic fluid into the system			8	3	3	72			No change of action