Safety, Reliability and Risk Analysis: Beyond the Horizon – Steenbergen et al. (Eds)

RAMS analysis: How reliability engineer and risk analysis tools can be applied to improve asset management on train life cycle

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ABSTRACT: RAMS analysis has main objective to define system availability, reliability and maintainability regarding critical equipment failures and safety issues like incidents and accidents which impact on system availability and employees health. On most of industries, the reliability diagram block is applied to model the complex systems. Regarding safety, in many cases, incidents are results of combined events which are better modeled by Fault three analyses. Nowadays the RAMS process phases is very well described in EN50126 by "V Diagram" regarding which activities is necessary in railways life cycle phases. Nevertheless, it is not clear which are the specific reliability engineer methods which must be applied in order to achieve high performance a long railways life cycle. The methodology described on EN50126 does not consider such application and integration of RBD and FTA as well as Monte Carlo Simulation. In addition, it is no mentioned others reliability engineer tools like accelerated test, growth analysis, Life cycle analysis a long enterprises life cycle.

Furthermore, regarding Safety, the Preliminary Hazard Analysis has been the most qualitative risk analysis applied to define hazard events but in most of cases such events are not quantified by FTA and when such events are modeled do not take into account the incidents effect on system availability. On Transportation Industry, the RAMS process analysis carries out RAM and safety access separately. This paper propose to integrate incident and equipment failures which affect System availability by RBD and FTA model and Monte Carlo Simulation in order to find out all events that causing System unavailability as well as define all incidents events which cause employees health damage. Thus, a case study will be carried out to exemplify Integrated RAMS analysis Methodology applied to Train system in project phase regarding Reliability Diagram Block, FMECA and FTA which model equipment failures and incident which impact in System availability. Such incidents modeled by FTA are integrated in Reliability diagram block. Therefore it'll be possible to compare system availability and reliability without and with incidents as well as identify equipment and event bad actors to improve system availability and safety error. In addition such methods can be carried on in also in operational phases in order to keep system high performance.

1 INTRODUCTION

The RAMS process described on Standard EN 50126-1 and EN 50126-3 define well all enterprises phases and which activities are necessary in each phases. Despite a very good phases and activities description it is not clear which Reliability Engineer tools must be implemented in each phase.

In addition on of the most important methods like RAM analysis is not explicitly defined by direct simulation application and despite that, is proposed to use Inherent Availability as system availability target.

Indeed, different professionals have different understood about concepts and consequently RAM analysis in many cases do not lead to best result due have not best reliability tools implemented in correct enterprise phase.

Actually, the train system has different systems with different reliability and safety requirement that demands different targets as well as methods applications.

System like bogie and brake for example has the reliability related to safety because many of such equipment failures are unsafe failures that trigger accident.

By the way round, other Systems like windows, toilet, and baggage support for example have no impact on train operational availability or safety in case of failure. Even though, such system requires performance index based on warranty.

The remarkable issue to be discussed is the integration of RAM and safety in some cases in order to show the safety impact caused by accidents on operational availability as well as maintenance policies impact on operational availability and safety (risk mitigation).

This paper will define the best Reliability Engineer approaches and methods to achieve the best performance in Train availability and focus on RAMS analysis due to such analysis importance along the whole enterprise phase and important train systems analysis cases will be carried out.

2 RAMS PROCESS

The RAMS process is a recognized management and engineering discipline for the purpose to guarantee the specified functionality of a product or service over its' complete live cycle, and to keep the operation, maintenance and disposal costs at a predefined accepted level, by establishing the relevant performance characteristics at the beginning of the procurement cycle, and by monitoring and control of their implementation throughout all project phases (Vozella, 2006).

The general definition of reliability, availability, maintainability, risk and safety used throughout industry and quoted in many engineering books published on this subject follows the example as taken from MIL-STD-785.

Reliability: the ability of an item to perform a required function under given conditions for a given time interval.

Availability (Instantaneous): ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.

Maintainability: a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.

Risk: undesirable situation or circumstance that has both a likelihood of occurring and a potential negative consequence on a project.

Safety: system state where an acceptable level of risk with respect to:

- fatality;
- injury or occupational illness;
- damage to launcher hardware or launch site facilities;
- pollution of the environment, atmosphere or outer space; and
- damage to public or private property.

Mostly safety and reliability issues are assessed separately for different approaches. In order to access safety, Risk Analysis methods like FMEA and PHA for example are the first step to assess system hazards. By the other way round, to access reliability, availability and maintainability is carried out RAM analysis. Despite effective methodologies, whenever is necessary safety and RAM must be integrated in order to achieve better results.

On Railway industry the standard EN 5126 supply a guide line of each step to carry on RAMS analysis in each enterprise phase like shows Figure 1.

In all V diagram phases RAM and Risk analysis are carry out in order to achieve high performance system. The next two items will specify each method that must be carrying out by RAM and Risk Analysis.

The first step in RAM process is "Concept" and it is necessary to define the impact of RAM tasks in enterprise as well as define reliability, availability and maintainability targets. Such definition will take high influence on whole enterprise phases as well as KPI targets. Is advisable to take into account similar project as reference but is also necessary to consider the new enterprise environments and customer requirement. The reliability concept is the ability of an item to perform a required function under given conditions for a given time interval. In many cases reliability is miscalculated or misunderstood. It is important to understand the reliability concept that is one of the most important targets to compare different equipment performance as well as to set up warranty requirement. Many companies in Railway Industry do not understand the reliability concept and define constant failure rate or MTBF as target for systems and equipment. Such targets are applied only for some electronics

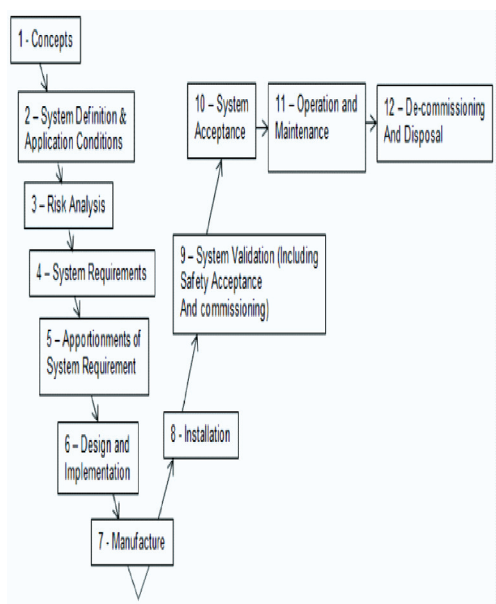

Figure 1. V diagram.
Source: EN 50126.

or electric component that fits well to exponential probability density function. That is not the repairable equipment cases which have wear out requiring preventive maintenance on most of cases to avoid failures. Even though, for electronic component reliability is a better target.

The following important concept is "Maintainability" the chance of performance maintenance in an expected period of time under given conditions and using stated procedures and resources. The remarkable point in repair time is that some companies do not consider the complete downtime time that equipment under repair cause in system operational availability. Actually, the repair time is the effective time to carry on maintenance or even take place the defected equipment for a new one. On both cases is required a time before start repair to access and check out equipment. Such tasks requires that system is not in operation state as well as additional time is required to start up equipment after repair. Such total time must be taking into account in order to predict the correct downtime caused by maintenance on system operational availability whenever specific equipment is under maintenance.

The third and most important concept is availability. There are different types of availability index and the most common used as target are Operational Availability, Average Availability, Instantaneous availability and Inherent Availability.

The "Operational Availability" means the percentage of total time that equipment, subsystem or system is available. That's represented by equation

$$A_o = \frac{\text{Uptime}}{\text{Total operating cycle time}}$$

or

$$D(t) = \frac{\sum_{i=1}^{n} t_i}{\sum_{i=1}^{n} T_i}$$

where:

t_i = real time in period i when system is working

T_i = Nominal time in period i

The operational availability comprises both reliability and maintainability concept and influence in availability targets.

The "Punctual Availability" means the probability of equipment, subsystem or system to be available in specific time t. That's represented by equation:

$$A(t) = R(t) + \int_0^u R(t-u)m(u)du$$

where

$R(t)$ = reliability

$R(t-u)$ = the probability of corrective action be performed since failure occur.

Such Punctual availability is important to support decisions as probabilistic results. Due to be hard to calculate such values can be defined by software applications.

The "Inherent Availability" means the operational availability which considers only corrective maintenance as downtime. That´s represented by equation.

$$A_i = \frac{MTTF}{MTTF + MTTR}$$

The remarkable point to be discussed on Inherent Availability concept is that the main assumption to apply such concept is that equipment is identical and independent distributed. Independent means that equipment repairs when failure occurs will not influence on following failure, in other words, equipment is always as good as new. Such assumption can be taken into account for equipment that is replaced whenever fails happen and no repair is carried out. Such conditions are assumed for electronic devices for example. Even in this case, is necessary to assume that environment condition where equipment operates is constant along time that is also not true for many cases.

To be identical is necessary that equipment belongs to the same population and that means similar production line, under same production conditions, transport and stock. By this way, equipment that replaces the fail one will have similar probability density function. Case of electronics component we regard exponential PDF.

Independent to discussion about environment conditions and similarity on product population such assumption can be tested. The Laplace test for example is a good test to show if failures along time increase decrease or have no tendency (stationary). Performing such test is possible to prove that equipment have improvement or degradations after repair, that happen on most of cases on repairable equipment. By this way "Inherent Availability" is not a good target for repairable equipment, repairable system or even system with repairable and no repairable equipment.

The operational Availability is indicated to be the main key performance target as well as reliability and cumulative number of failures. Regarding that such target are dependent on time and **"Train System"** is a complex system to model with many parallel configurations is recommended to model such system an subsystem by reliability block diagram and run direct simulation by using software.

The cumulative number of failures is also an important index and regarding repairable system, is possible to consider degradation when the renewal process model or Power law models are applied.

The next step on V diagram is **"System Definition and Application condition"** and in such phase is necessary to carry on RAM analysis based on past experience and available data of similar equipment as well as regarding operational and maintenance condition and additional constrain.

Depends on available data to carry on life cycle analysis, in some cases the RBD will regards equipment level due lack of data about component. That is not a limitation because in this phase the main objective is defined operational availability, reliability, maintainability and cumulative number of failure. Whenever no failures are available is necessary to consult specialist to estimate equipment PDF type and parameters.

When carry on RAM analysis by software is also possible to use the FTA models. The main difference between RBD and FTA is that RBD enable to model complex configuration that is not possible by FTA. Figure 2 below shows RAM analysis methodology.

The first step on RAM analysis is to define scope of analysis and in Train case means to define type of train as well as subsystems. All subsystems which impact on system (Train) operational availability in case of failure must be modeled on System RBD. There are systems which impact on system operational availability as well as safety like brakes

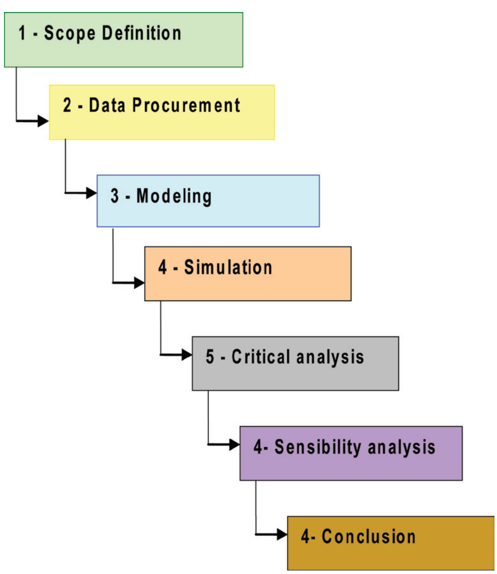

Figure 2. RAM analysis methodology.
Source: Calixto, 2013.

and bogie. Other systems have particular failure modes which impact on safety like failure open in doors case and such event can be modeled by FTA and be taken into account on risk analysis.

In addition there are systems which their failures cause no impact on system operational availability as well as insignificant impact on safety like toilet, windows, passenger system communication, radio, etc. Even though, is important to have key performance factors like operational availability, reliability, maintainability and cumulative number of failure for such equipment in order to check performance established on warranty. In such cases, is not necessary to break down such system in subsystem and a simple solution is to model RBD in equipment level.

The next step after scope definition is life cycle analysis and is required to access historical failures data to carry on statistical analysis in order to define equipment PDF parameters as well as consult specialist opinion when such data are not available.

The follow step is Model system and two main models came out that are RBD and FTA. Actually for similar system where most of configurations are in series or in parallel is possible to uses both models but in case of complex configuration that looks like a net, is advisable to model by RBD. The additional point is that many FTA model do not enable the possibility of regards maintenance policies and that is a limitation for repairable systems.

The following step is simulation and direct simulation gives different results like operational availability, reliability, cumulative number of failure, number of preventive maintenance, number of inspections, cost of preventive maintenance, cost of corrective maintenance and total cost. It is necessary to take into account all maintenance policy defined in RCM analysis.

The critical analysis is care out as result of simulation where is possible to detect which subsystem and equipment have more impact on system operational availability and system reliability.

The sensitivity analysis has the main objective to highlight the system weakness and vulnerability. Thus is possible to test the stock policies, redundancy configuration as well as impact of other system.

The least and no longer less important step is conclusion and the main objective is to show the main opportunities of improvement to managers in order to improve system performance.

The next phase in RAM analysis is **"System Requirement"** that is result of RAM analysis, customer requirement and a combination of both. Is important here that the RAM process is clear as well as key performance factors stated as target in warranty contracts. Based in such requirements the equipment supplier will be selected to supply equipment to whole system. The RAM program must be established in order to keep track all following steps.

The next phase is **"Apportion of system requirement"** and in this phase is necessary to define system components key performance factors.

On both phases is necessary that suppliers prove their key performance data based on historic data or even accelerated test.

Once selected suppliers for all system the next phase is **"Design Phase".** Regarding that all previous phase were successful, design is one of the most important phase because all guarantee index is achieved or not depending on performance achieved in such phase. The KPI are the main target to system design and whenever is necessary to achieve such index, quantitative accelerated test, HALT, HASS and Reliability Growth Program must be applied to do so. One of the most important methods applied on design is the "DFMEA" because focus on failures caused by bad material quality, bad design, bad configuration. Thus is possible to drive improvement in design phase based on specialist experience of past product that is stated on DFMEA.

The logistic factors must be also regarded by Integrated Logistic Support in design phase and that means regards stock cost, deliver time, and impact of such factors on system operational availability.

Other important issue is to define the critical failure of equipment that impact system. Thus, is necessary to carry out process FMECA and based on FMECA failure mode is enable to add the maintenances policies tasks and carry out RCM analysis. As mentioned before all maintenance policies will be taking into account in RAM analysis in put on RBD model.

The next phase is **"Implementation"** and once designs of systems are approved and achieve the KPI target, all system, subsystem and components configurations can be defined and established to be manufactured.

The next phase is **"Manufacture"** is very important to take into account the production line effects on equipment reliability. Thus, is also important to consider which are the best production condition for equipment based on it characteristics in order to avoid bad production effects on equipment reliability. The equipment must be tested after production and if necessary the production as well as product must be modified. A remarkable method to support such decision in this phase is FRACAS analysis which will detail the failures and their root causes.

The next phase is **"Installation"** and it is very important to take care of human error in assembly systems that may have bad influence in systems reliability. Some of probable human error can be identified by DFMEA as well as process FMEA. Is advisable to take into account such human factors and in some cases human reliability analysis are recommended to access probable human error in system assembly by define human error probability as well as human performance factors which have more influence on human error.

The next phase is **"System Validation"** and the main objective is update RAM analysis with real data from systems and their equipment. Therefore is essential to carry out life cycle analysis with real failures.

After validation the next phase is **"System Acceptance"** and the main objective is to accept or reject system performance based on warranty index (Operational Availability, Reliability, maintainability and cumulative number of failures).

The systems that are not approved must be take place or improved. On first case, low performance system cause is explained by some mistake on project, process or transportation that affected systems reliability and if take place for usual similar system that is expected to achieve the index established on warranty. On second case, when the system do not achieve index established on warranty even when a new one is take place. In such cases is necessary to carry on Reliability Growth Program to certify that reliability as well as other index like operational availability, maintainability cumulative number of failures will be achieved.

After successful acceptance the project can be considered finished and **"The Operational and maintenance"** phase starts. In his phase is necessary update the RAM analysis whenever the life cycle analysis is updated. Furthermore is also necessary to update the RCM analysis in order to have best maintenance policies which lead to best system availability performance.

Is also important to update RAM analysis whenever system is modified and a long operational phase a **"Reliability Data Bank"** must be making up to support futures RAM analysis or similar projects. The final and one of the most important analyses is the **"The Optimum replacement time"** and such analysis must take into account reliability as well as operational cost. Whenever is detected increased operational cost the equipment must be take place.

3 INTEGRATED RAMS PROCESS

The RAMS process proposed regards the best Reliability Engineer and Risk analysis practices a long enterprise phases.

As mentioned before, once defined system target like Operational Availability, Reliability, Cumulative Number of failures and risk based on life cycle analysis, RAM analysis and Risk analysis the next step is to carry on select supplier and confirm their index based on warranty. In order to anticipate problems in validation phase and additional project cost all effort in design phase must be carry out in order to systems achieve targets specified. In some cases, in order to predict new product reliability as well as robustness the quantitative accelerated test and HALT must be necessary. In case that such system do not achieve reliability, operational availability, cumulative number of failure, The Reliability Growth program in design phase is necessary. Figure 3 shows the proposed methods that must be applied a long Train enterprise.

A long operational phase is necessary update reliability data, RAM and Risk Analysis as well as RCM analysis in order to have the best maintenance policy to guarantee system availability and safety.

The Optimum replacement Time for all equipment must be analyses in order to reduce operational cost, keep system with high availability and under acceptable risk level.

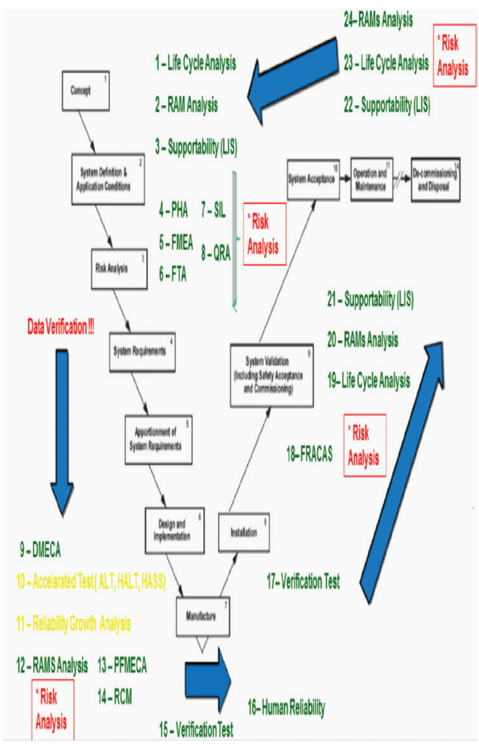

Figure 3. RAMS proposed methodologies.

One of the most important methods is RAM analysis that is a driver on the beginning of enterprise to define index, essential to be assessed on design phase in order to check he subsystems impact on the whole train, essential in validation and acceptance phase when such analysis is updated by real data as well as in operational phase which drives system performance and bad actors equipment definition to implement improvement. Thus, the next item will focus on two RAMS analysis case.

4 RAMS CASES APPLICATION

4.1 *Pantograph system RAM analysis*

One of the most important subsystem in Train system is "Pantograph" and the main function is to provide energy by electricity line contact. Most of Pantograph equipment causes impact on operational availability and there are not unsafe failures with catastrophic consequences. The Pantograph subsystem is a very good example of RAM methodology because requires life cycle analysis, FMECA, RCM analysis RAM analysis.

In fact as repairable system is necessary to regards maintenance effect of operational availability. Thus, after carry out FMECA, RCM and lifecycle analysis the next step is to model RBD to define which events impact on Train operational availability. Figure 4 shows Pantograph RBD regarding all equipment that causes impact on Pantograph operational availability. Indeed, the Frame (and insulator), valve plate, Elevation, arm and collector head are the most important equipment.

In order to prevent such failures different preventive maintenance and inspections are carried out depends on equipment.

The next step is to carry on direct simulation of such RBD model and find out the failures, inspections and maintenance impact on operational availability. Table 1 shows the direct simulation result for two years.

Based on RAM analysis result the most critical equipment is the carbon strips and to avoid such equipment fail is necessary to carry on twelve preventive maintenances in two years. If such preventive maintenances are not carried out is possible to reduce maintenance cost in more than 50% but consequently there will be higher risk to have a failure in pantograph and stop train during passenger service.

In order to maintain such high level of operational availability and reduce maintenance cost is necessary to have more reliable carbon strip or even improve such equipment reliability by reliability growth program.

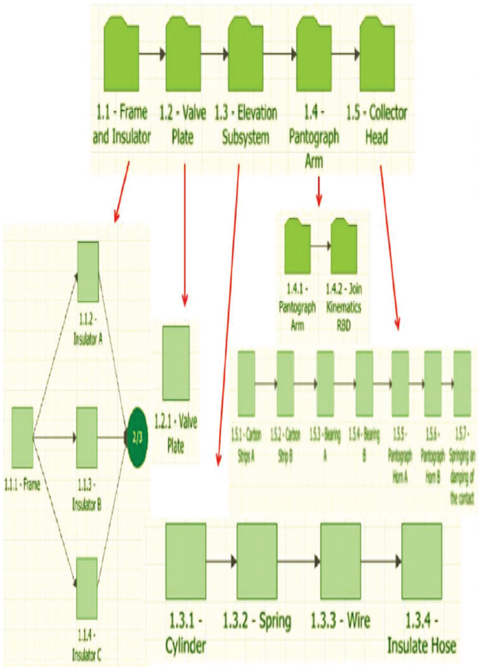

Figure 4. Pantograph RBD.

Table 1. Pantograph direct simulation result.

With preventive maintenance	
Mean availability (all events):	0.9999
Std deviation (mean availability)	0.00E + 00
Mean availability (w/o PM, OC & Inspection):	1
Point availability (all events) at 14700:	1
Reliability (14700):	1
Expected number of failures:	0
Std deviation (number of failures):	0
MTTFF (Hr):	21207617
System uptime/downtime:	
Uptime (Hr):	14698.15
CM downtime (Hr):	0
Inspection downtime (Hr):	0.649148
PM downtime (Hr):	1.198096
OC downtime (Hr):	0
Total downtime (Hr):	1.847244
System downing events:	
Number of failures:	0
Number of CMs:	0
Number of inspections:	16.269
Number of PMs:	11.653
Number of OCs:	0
Number of OFF events by trigger:	0
Total events:	27.922
Costs	
Total costs:	8419.44

4.2 *Bogie subsystem RAMS analysis*

Another important subsystem in Train system is “Bogie” and the main function is to provide train movement by railway contact. Most of Bogie equipment do not cause impact on operational availability but some of them impact operational availability in case of failure and can also cause a catastrophic accident. The bogie subsystem is a very good example of RAMS methodology because requires life cycle analysis, FMECA, RCM analysis RAMS analysis as well as FTA to model accident.

In fact as repairable system is necessary to regards maintenance effect of operational availability as well as in risk mitigation. Thus, after carry out FMECA, RCM and lifecycle analysis the next step is to model RBD and FTA to define which events impact on Train operational availability. Figure 5 shows bogie RBD regarding all equipment that cause impact on Bogie operational availability. Indeed, the wheels, axles, axle boxes, frame and Obstacle detector are the most important equipment. Actually, such components have unsafe failure depends on level of failure degradation for example crack on axle.

In order to prevent such failures different preventive maintenance and inspections are carried out depends on equipment.

The derailment block regards a combination of event which can also trigger derailment like air spring deflated, track twist and loss of all primary suspension. In this case, FTA is a good representation for derailment as shows Figure 6.

The FTA as well as RBD model is able to consider all failure modes PDF, all repairs time PDF

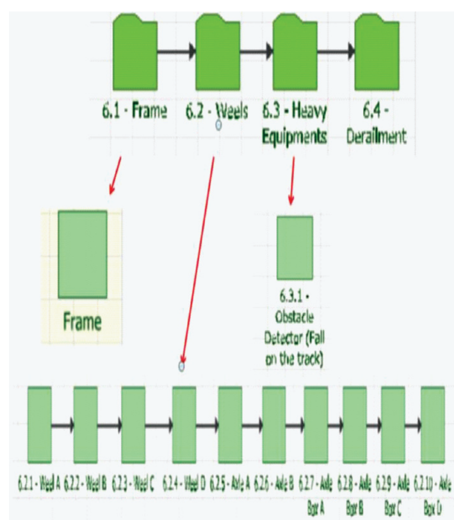

Figure 5. Bogie reliability block diagram.

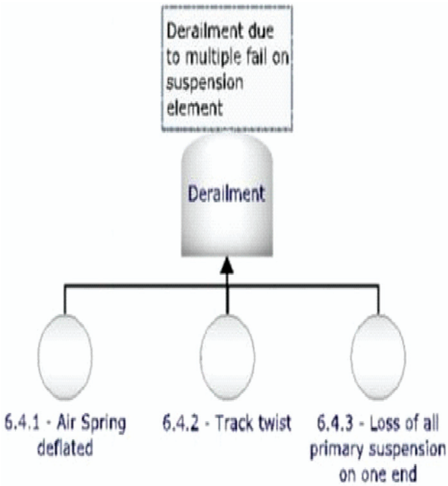

Figure 6. Fault tree analysis (derailment).

and maintenance policies. Despite such possibility is not possible to represent complex system by FTA and whenever face such limitation is advisable to model such system by RBD.

The next step is to carry on direct simulation of such integrated model and find out the failures, inspections and maintenance impact on operational availability. In addition is also possible to analyze safety impact on operational availability as well as maintenance impact on risk mitigation.

The RAM analysis result shows that system achieves 99.94% of operational availability along the whole operational life (10 years). Such operational availability is achieved based on inspection and preventive maintenance policy that the whole cost is double of system without preventive maintenance policy. The main point is if system has no preventive maintenance policies means that some possible catastrophic accident may occur. Actually the direct simulation regards the maintenance policies and inspections are able to detect and anticipate all failures that it is not total reality in real life.

Thus, the best approach is to try to achieve the balance between inspections and maintenance policy and critical equipment reliability. Therefore is necessary to predict reliability on design phase as well as define reliability in operational phase based on maintenance reports.

5 CONCLUSION

Nowadays to apply RAMS process a long Train System enterprises faces a big challenge due different subsystems technologies involved, number of specialist and different knowledge levels about reliability and risk analysis methods.

Because such enterprises requires high investment and in case of failure can produce accident with consequence for the whole society such reliability engineer and risk analysis methods are essential to enable profits, reliable and safe trains.

Despite most of Reliability Engineer and Risk analysis methods are spread out in many industry all over the world, in Railway Industry such methods are not completely understood as well the benefits for their application.

In addition, the correct success of such methods application required a very well RAMS process established as well as Reliability and Risk Analysis Specialist.

Even though such RAMS process is successfully defined and Reliability and Risk Analysis professional are hired is necessary to consider the RAM and Safety integration as well as RAMS process integration with other Management process like Project Management which has high influence on RAMS process.

Despite the good results that RAM Analysis is able to provide the other Reliability methods in design phase like Quantitative Accelerated Test, HALT, DFMEA and Reliability Growth Analysis are essential to provide more reliable equipment in order to reduce maintenance cost as well as mitigate risk.

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