“RAM analysis methodology is the basis for railway asset performance prediction: The Pantograph system case study”

Abstract: ***This business paper aims to demonstrate the application of RAM analysis for railway industry as part of RAMS program implementation, which enable to predict the railways asset reliability, availability and maintainability in different levels, such as system, subsystem, equipment and component by taking into account the relation to each part failure to the impact to the highest system level. The basis for the RAM analysis, prediction is the LDA results based on historical data as discussed in business paper presented in March 2018 in the ECC website. Therefore, to predict the railways system performance, after the LDA results, it´s necessary to model the systems based on the RBD (Reliability Diagram Block) or FTA (Fault Tree Analysis). The final step is the Monte Carlo simulation concerning the system life cycle and operational profile. Finally, the RAM analysis results will provide more than systems, subsystem, equipment and component performance, but also the bad actors definition, in other words, the equipment/component which causes more impact on system operational availability. In order to exemplify the RAM analysis methodology, the case studies applied to critical equipment such as Bogie, Break and signalling will be presented at the end of this chapter.***

Key Words: Lifetime Data Analysis (LDA), reliability, availability, maintainability, expected number of failures and life cycle cost.

(This paper is fully described in the book “RAMS and LCC engineering: Analysis, Modeling and Optimization (Chapter 7). Author: Dr. Eduardo Calixto)

1 - Introduction

The RAM analysis aims to predict the system performance to support the leader´s decision about the railways system performance target definition during the concept phase, which need to be verified during the design phase and validated during operational phases. During the design phase, the RAM analysis enables also to compare different system configurations and verify the achievement of performance. In addition, the RAM analysis also supports the RAM engineers to predict the rail asset future performance during the operational phase based on the current equipment/component reliability and maintainability prediction (LDA).
By applying RAM analysis, it´s possible to find out quantitatively system availability, reliability, and equipment maintainability and which critical subsystems and equipment influence system performance the most. The RAM analysis can be performed for a complex

system with several pieces of equipment or going deeper and assess a single piece of equipment with several components.
Despite of the most popular reliability engineering methods, the RAM analysis concepts are still a point to be clarified and discussed. Despite of the large RAM analysis application in different industries including railways, some concepts are misunderstood or wrongly applied. Therefore, a clear definition of the different types of availability will be presented as follows:

- Punctual Availability;
- Average Availability;
- Permanent Regime Availability;
- Inherent Availability;
- Achieved Availability;
- Operational Availability.

The Punctual Availability is the probability of a piece of equipment, subsystem, or system being available for a specific time t, and in case of failing, the equipment will be repaired during the expected interval of time. The punctual availability is represented by:

$$A(t) = R(t) + \int_{0}^{u} R(t-u)m(u)du$$

Where,

R(t) = reliability.

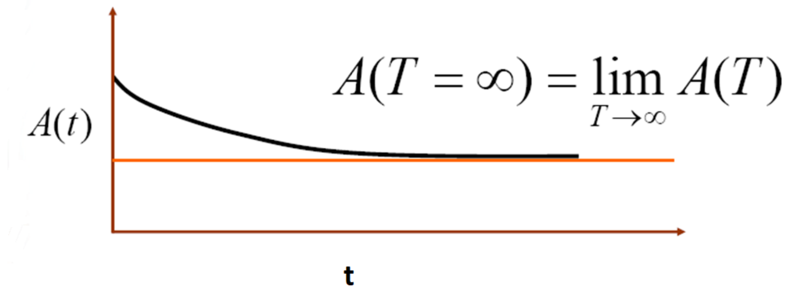
R (t-u) = Probability of corrective action be performed since the failure occurred.

m(u) = renewal density function.

The Average Availability is the punctual availability average over time, represented by:

$$\overline{A(T)} = \frac{1}{T}\int_{0}^{T} A(t)dt$$

The Permanent Regime Availability is the availability value when time goes to infinite, represented by:



The Operational availability is the percentage of total time that a piece of equipment, subsystem, or system is available, represented by:

$$A_o = \frac{\text{Uptime}}{\text{Total Operating Cycle Time}}$$

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 the system is working

T_i = Nominal time in period i

Inherent availability is the operational availability that considers only corrective maintenance as downtime, represented by:

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

Achieved availability is the inherent availability that considers preventive and corrective maintenance as downtime, represented by:

$$A_A = \frac{MTBM}{MTBM + \overline{M}}$$

Where:

MTBM =mean time between maintenance

$\overline{M}$ = preventive and corrective downtime time

The Operation availability is the most proper availability performance index definition to be applied in railway system because take into account the total downtime caused by equipment failure or preventive maintenance at system total life cycle time. Such index can be measured in daily based and have a direct relation with the equipment/component reliability and maintainability which enable the operational availability prediction.

The inherent availability is defined as a performance target in many projects, which may cause a problem when compared with the real operational availability, when the asset is operating. In fact, the inherent availability can be lower than the real operational availability, which will lead a false performance assessment. Therefore, the operational availability is the most proper availability definition to be used to assess railway system because can be compared with the real system performance as well as predict future performance based on RAM analysis.

The RAM analysis must be applied throughout the railway asset life cycle as a tool of verification and validation that enable to assure that the design achieves the performance target as shown figure 1.

During the concept phase, it´s important to have a high-level verification of the system performance. Therefore, it´s possible to compare different technologies in system level, but not in equipment and component level if there´s no data available. In addition, it´s very important to verify if the reliability requirement is feasible to be achieved concerning the expected number of failures and life cycle cost. The RAM analysis, recommendation during concept phase need to focus on verification of the reliability requirement in high level as well as the assessment of different technologies.

During the design phase, it´s important to update the RAM analysis (RBD model) based on a new configuration and modification throughout the design phase. In this phase the type of technology is already defined, but the configuration of equipment and the component need to be discussed. Therefore, the RAM analysis is the basis for such verification and need to propose recommendation concerning the best equipment and component design configuration to the system reliability achievement. As discussed before, it´s very important to define reliability requirements for equipment and component.

Finally, during the operation phase it will be possible to update the RAM analysis model with real historical failure data collected during the operation phase Therefore, the system, equipment and component performance will be validated. The RAM analysis, recommendations during the warranty phase has the main objective to propose the necessary modifications and improvement for the system achieve the defined reliability and operational availability target. In addition, whenever any modification or new maintenance policy is discussed during operation phase, the RAM analysis may be implemented to verify the proposed solutions and recommend the one which allows the system to achieve the required reliability and operational availability performance.

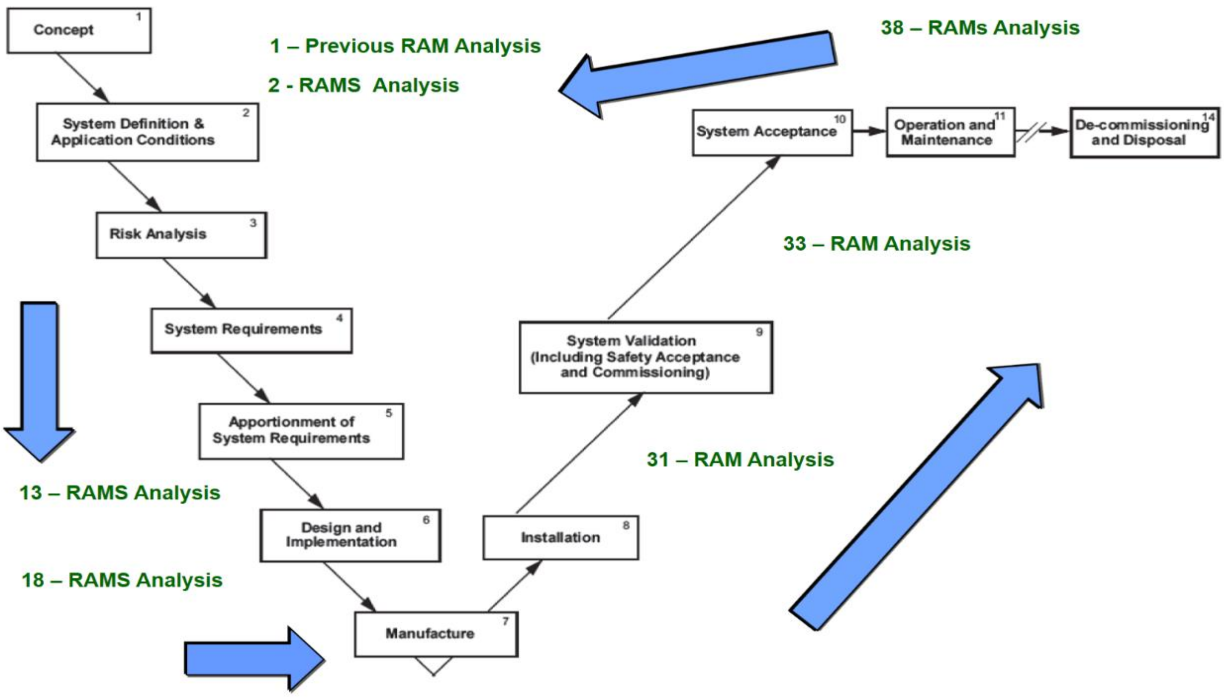


Figure 1 RAM analysis throughout the Asset Life cycle phases

2 – RAM analysis Methodology (RAM)

The RAM analysis methodology application requires a very disciplined and organized process concerning the railway asset under scope to get the proper result in a proper time. Unfortunately, many RAM analysis does not achieve its objective because of the lack of reliability and maintainability information or due to poor definition of the objective and scope. All such aspects supposed to be considered during RAM planning and to be anticipated to avoid delays and misunderstood. In order to implement the RAM analysis effectively, the seven steps as shows figure 2.

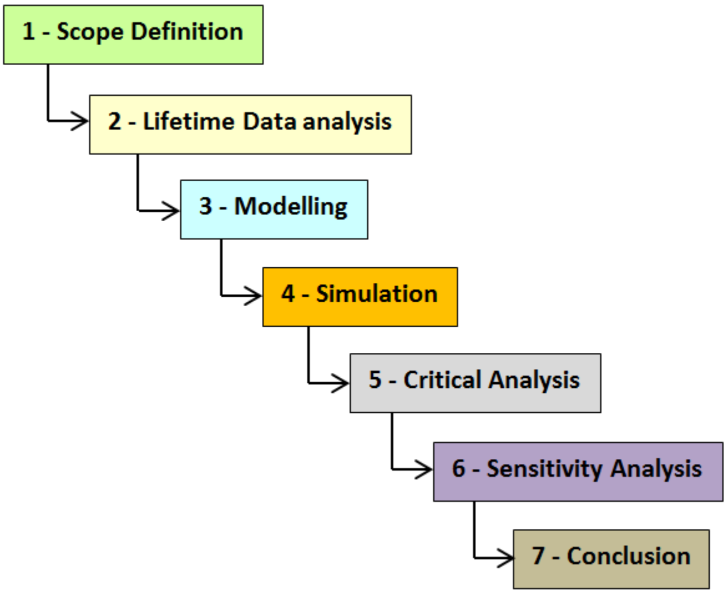


Figure 2 RAM analysis methodology

3 – Reliability Block Diagram (RBD)

After defining all reliability and maintainability data, the system model phases can start. The reason to start this phase only after all reliability and maintainability data are ready to be used is to avoid delays RAM analysis or loss of time by performing a RAM analysis without reliable data. Unfortunately, what happens in many cases is that engineers start to model their system first without having all reliability and maintainability data or even a clear idea about which equipment/component must to be modelled.
Therefore, in addition to have the reliability and maintainability data, the list of equipment that must to be part of the RAM model and in which level must be clear and formally defined. In fact, a clear list of equipment to be used during RAM Model requires also an understanding about each equipment failure in system performance as will be defined later in this item the so called “Model Assumption List “.
A model represents a system behavior under specific conditions. In RAM analysis, context, the usual models which represent system during operation are RBD and FTA.
On both cases, the model represents the relation of each equipment/component failure and the impact on the system performance. The FTA analysis will be demonstrated in chapter 9, which relates to safety issues. Concerning RBD, each component/ equipment which causes direct impact on the system performance when fails is represented as a series block. In addition to series block configuration, different combination of more than one equipment/component are represented in parallel as the simplest case as shows the figure 3.

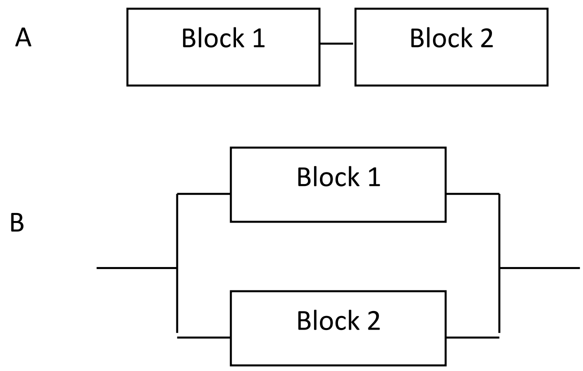


Figure 3 RBD configuration

In order to predict the system reliability and operational availability the follows mathematic rules need to be taking place.
In figure 7.3, case A, system reliability is represented in series and is described mathematically by:

$$R_{System}(T) = R_{Block\ 1}(T) \times R_{Block\ 2}(T)$$

In case of identical equipment/component represented by series configuration, system reliability, which includes n blocks, the system reliability will be:

$$R_{system}(T) = \prod_{i=1}^{n} R_i(t) = R(t)^n$$

Where,
n = number of blocks

In figure 8.3, case B, system reliability is represented in parallel and is described mathematically by:

$$R_{System}(T) = \left(1 - R_{Block\ 1}(T)\right) \times \left(1 - R_{Block\ 2}(T)\right)$$

The same concept applied to predict the reliability of blocks in series or in a parallel is applied to calculate the system operational or Inherent availability.
In case A, availability is represented in the series and is described mathematically by:

$$A_{System}(T) = A_{Block\ 1}(T) \times A_{Block\ 2}(T)$$

In case B, availability is represented in parallel and is described mathematically by:

$$A_{System}(T) = \left(1 - A_{Block\ 1}(T)\right) \times \left(1 - A_{Block\ 2}(T)\right)$$

One of the most important concepts of the system configuration concerning RBD is the effect of lower reliability blocks in series configuration. ***Whenever the system is represented by RBD blocks in series, the system reliability (availability) will be equal or lower than the lowest reliability(availability) block value.*** This is one of the most important concepts in RAM analysis, because with blocks in series, the lowest availability will always be the most critical to system availability and the first to be improved. In addition, when improving the system and achieving availability targets may be more than one block must be improved. Therefore, when the reliability increases are highly costly the redundant configuration must be assessed as will be discussed in item 7.2.6.
In case n, identical parallel blocks and system availability requires k of n blocks at the same time. The system reliability can be represented by:

Where:

$$R_s(k, n, R) = \sum_{r=k}^{n} \binom{n}{r} R^r (1 - R)^{n-r}$$

K = Number of parallel blocks required;
n = Number of parallel blocks;
R = reliability

Other parallel configuration type with independent effect is the standby. In such configuration one block is active and other in parallel is inactive. Whenever an active block fails, the inactive block takes place to avoid system unavailability. The usual example of such configuration of the railways Industry system is the IP and WTB communication cables, which usually have two installed. One operates and the other one is the standby. The Parallel configuration is mathematically represented by:

$$R(t)=R_1(t)+\int_0^t f_1(x).R_{2,inactive}.\frac{R_{2,active}(t_2+t-x)}{R_{2,active}(t_2)}dx$$

Where:

$R_1(t)=$ Reliability of active block

$f_1(t)=$ PDF of active block

$R_{2,inactive}(t)=$ Reliability of standby block when active block is operating

$R_{2,active}(t)=$ Reliability of standby block when active block is not operating

$t_{2,}=$ Standby operating time

If we consider the effect of the switch which enable to change from active block to standby block that is called "switch effect", we have:

$$R(t)=R_1(t)+\int_0^t f_1(x).R_{2,inactive}.\frac{R_{2,active}(t_2+t-x)}{R_{2,active}(t_2)}.R_{sc,inactive}(x).R_{Sc,required}(x)dx$$

Where:

$R_{sc,inactive}(t)=$ Reliability of switch on standby condition

$R_{sc,required}(t)=$ Reliability of switch when required to operate

4 – Monte Carlo Simulation

After model the System RBD based on assumption model list, the next step is the simulation, which means to verify the performance result based on system profile features such as lifetime period, system percentage of usage, number of simulation and phases.

In railways industry the lifetime period can be defined in Km or in year time. The important issue when a system such as train, locomotive or ERTMS are model is to have in mind that all equipment/ component supposes to be a similar type of lifetime period. Usually, the km is the most used lifetime period for railways assets because many of them do not operate 24 hours per day, 365 days per year. Therefore, the km describes the operational lifetime of such assets. In order to facilitate the model and the understanding about the involved parts to verify and validate the railways asset performance, in many cases a conversion from Km to years take place and the system performance is expressed in years (or hours).

The second important aspect of the railways system lifetime profile is the usage or duty cycle. The duty cycle is the percentage of the time that a system operates during a cycle of time, which can be defined in years, hours or other time variable depends on the system life cycle. Some examples of duty cycle lower than 100% is the Auxiliary Power Unit in locomotive, and the battery in trains. For urban trains, on most of the cases they operate from 7am to 12pm, having six hours of every day. Such hours are used to perform emergency maintenance and repairs. Mostly the train fleet is planned to have some of the trains of to perform preventive maintenance along the life cycle.

The third aspect of the simulation is the number of simulations that need to be performed, which depends on the level of confidence in the final simulation result. Actually, there´s not a big discussion about the level of confidence in simulation results because any simulation which set up the number of simulation, higher than 200 is acceptable because higher than 200 simulation the final result will not chance significantly when compared to 200 simulations. In other words, all the simulations do is to replicate the calculation concerning the reliability and maintainability data input and the RBD model replicate several times and get the average of the results. The figure 4 shows an example of Monte Carlo simulation. In the middle of the figure, the yellow line shows the result variance, which after 200 simulations is irrelevant, represented by a straight line.

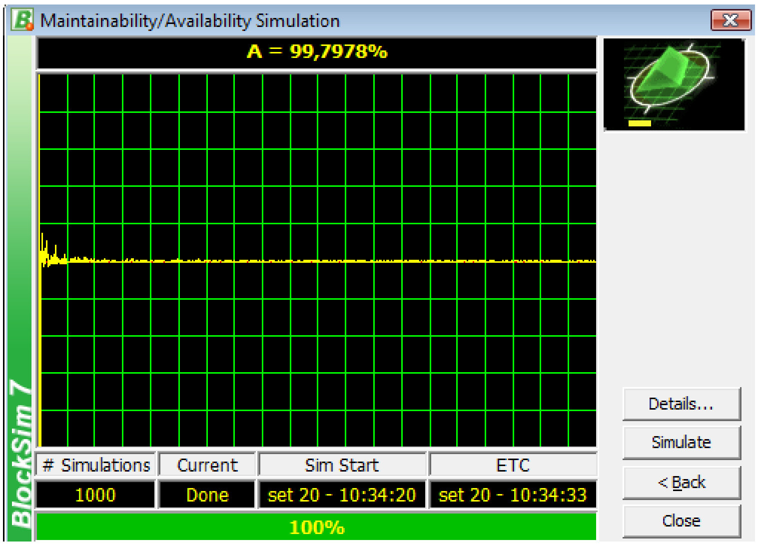


Figure 4 Monte Carlo Simulation (Reliasoft Blocksim Software)

The main issue concerning the simulation is to how to define the reliability and maintainability PDF values in RBD model.

The recognized approach to run simulation system is the so-called Monte Carlo simulation. Such a method allows data to be created based on the PDFs. For example, having a Weibull 2P (β,η), the following equation is used:

$$T = n\{-\ln[U]\}^{\frac{1}{\beta}}$$

Where:
U = random number between 0 and 1
T = time

When simulating a whole system, each block that represents one specific piece of equipment will have PDF for failure times and another for repair time as discussed previously. In this way, Monte Carlo simulation will proceed with failures over the simulation time for all block PDFs (failure and repair). In doing so, when a block fails and it's in series in the RBD, the unavailability will be counted in the system for failure and repair duration over simulation time. The figure 4 shows the concept of the PDF values and the effect of block unavailability on system availability during the Monte Carlo Simulation.

Based on the figure 4, the system operates until the first failure time (t = 4 hours) and takes around 4 hours to be repaired, and the second failure occurs at 12 hours. Based on each specific

PDF related to failure and repair for each individual block, the Monte Carlo simulation defines the values of failure time and repair time to be considered.
After the simulation the software delivers a result concerning the performance indexes achieved based on the defined lifetime profile as will be described in the next item.

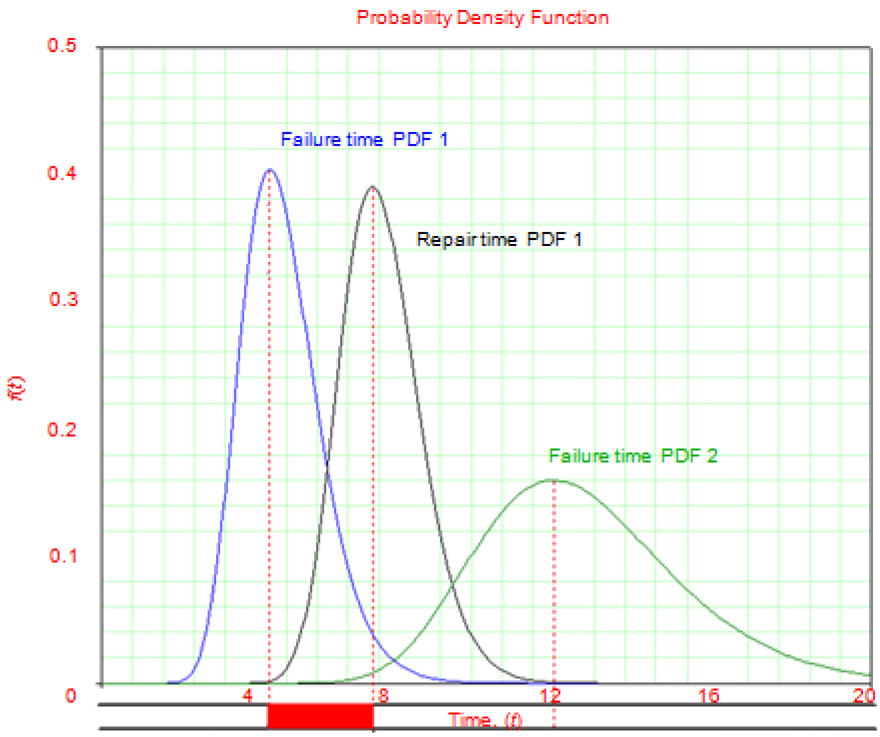


Figure 5 Monte Carlo Simulation (Block unavailability). Source: Calixto, E. et al 2015.

4 – Preventive Maintenance Modelling

The preventive maintenance has the important hole of preventing failure as well as to reduce the life cycle cost and downtime. Therefore, the preventive maintenance is applied if the downtime and cost is lower when compared to the corrective maintenance. In addition, the preventive maintenance is also applied independently of downtime and cost when it´s necessary to prevent an incident or accident. In fact, the type of equipment, which it´s feasible to apply the preventive failure is the mechanical parts, which have degradation failures and can be detected and prevented.
Since the preventive maintenance avoids the failure to occur, the reliability is recovered. The level of reliability recovery depends on the success of the preventive maintenance, which enable the repaired/replaced equipment to recover to the state between "as good as new" and as "bad as old", in other words, from 100% to 0%. The degradation after repair so called "The General Renovation Process" will be discussed in item 7.4. By now, it´s important to understand that the preventive maintenance can recover the equipment reliability. In addition, another important point is to have in mind that the preventive maintenance will never improve the equipment reliability, because the reliability is an intrinsic product feature.
Despite of having an important hole in failure avoidance, the preventive maintenance may affect the life cycle cost whenever it´s taken place much earlier than expected to avoid a specific

equipment failure. In fact, the extreme case is the early life failures, which the preventive maintenance will not eliminate the equipment low performance because the early life failures are associated with systematic failure causes such as mistakes during design, error during the manufacturing or human error during installation, operation or maintenance.
Another aspect, which influence on higher life cycle cost related to preventive maintenance is the early and high frequent schedule repair/replace defined by authorities or vendors. Unless it´s related to safety, the best practice of preventive maintenance, reliability and optimization must be applied to define the railways asset interval of repair/replace.
As discussed in chapter 3, the RCM is a very good method to define the type of preventive maintenance and the interval of intervention. The RCM analysis is an input to RAM analysis. Therefore, it´s possible to input all maintenance tasks related to time schedule in the RBD model and run the Monte Carlo simulation considering the preventive maintenance.
The figure 6 shows an example of the preventive maintenance input on the Pantograph´s power strap RBD model in the Blocksim software (Reliasoft). Other software tools such as Avsim (Isograph) and ApmOptmizer (BQR) have all some similar function related to preventive maintenance and inspection and can also be used for such type of assessment.
As discussed in chapter 3, the preventive maintenance does not apply to random failures, in other words, equipment with reliability PDF is defined as exponential. In this case, the reliability is not recovered after repair. By the other hands, if the electric or electronic, which is represented by exponential pdf in RBD model, is replaced for a new one, and the new one did not suffer any type of degradation before and during the replacement, the reliability will be recovery to the state as good as new.

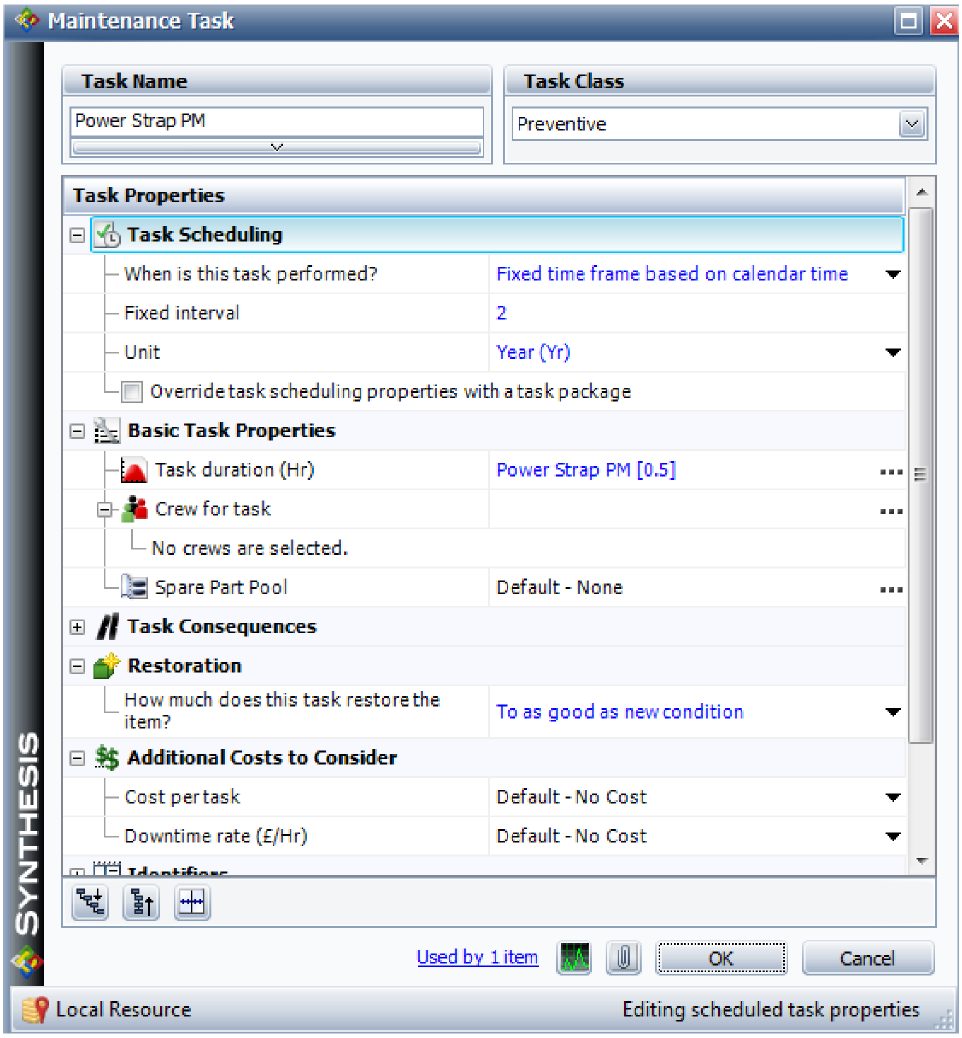


Figure 6 - Power Strap Preventive maintenance input in RBD model

As mentioned before, the recovery of reliability after maintenance range from the state as good as new to as bad as old. In the literature, there´s a misunderstood regarding such mathematic concept. The concept of the reliability recovery after preventive maintenance applied in the literature nowadays, states that the reliability recovery depends on the type of PDF. The reliability calculation when the preventive maintenance takes place to avoid the failure is represented by the equation below considering the simplest case of one preventive maintenance:

$$R(T) = R(t) \times R(T - t)$$

The final reliability (R(T)) will be the product of the reliability in the interval of time until the preventive maintenance (t) with the reliability related to the interval of time after the preventive maintenance (T-t). The figure 7 shows the reliability affected by preventive maintenance.
In the literature, for the cases of wear out phase, whenever the preventive maintenance is implemented before the wear out starts, the reliability will be recovered below the state as good as new. For the cases where the equipment reliability is represented by exponential PDF, there will be no recovery of reliability.
In order to demonstrate such concept, let´s consider the Weibull 2p with parameters β=3.04 and η=3.6. The reliability in 3 years is calculated based on the equation below.

$R(T) = e^{-\left(\frac{T}{n}\right)\beta}$

$R(3.04) = e^{-\left(\frac{3}{3.6}\right)3.04} = 0.5635 = 56.35\%$

Concerning the recovery reliability in the interval between 0 and T, the final reliability is the reliability before the preventive maintenance and after preventive maintenance. The reliability in 3 years will be the reliability in 2 years (t=2 year) multiplied by the reliability in 1 year (T-t = 1), which achieves 82.90% as demonstrated based on the equation below.

$R(T) = R(t) \times R(T - t)$

$R(T) = e^{-\left(\frac{t}{n}\right)\beta} \times e^{-\left(\frac{T-t}{n}\right)\beta}$

$R(3.04) = e^{-\left(\frac{2.0}{3.6}\right)3.04} \times e^{-\left(\frac{3.0-2.0}{3.6}\right)3.04}$

$R(3.04) = e^{-\left(\frac{2.0}{3.6}\right)3.04} \times e^{-\left(\frac{1}{3.6}\right)3.04}$

$R(3.04) = 0.8462 \times 0.9799 = 0.829 = 82.9\%$

The false concept in this assumption above is to define the reliability in the interval 0-T. In fact, what´s important to define is the reliability in the time T, in other words, the reliability after the preventive maintenance (T-t=1 year). Therefore, assuming the state as good as new after preventive maintenance, the reliability in T will be 97.99% as shows the equation below.

If,

$t_{apm} = time\ after\ preventive\ maintenance$

$R(T) = R(t_{apm}) \times R(T - t_{apm})$

$R(T) = e^{-\left(\frac{t_{apm}}{n}\right)\beta} \times e^{-\left(\frac{T-t_{apm}}{n}\right)\beta}$

$R(3.04) = e^{-\left(\frac{0.0}{3.6}\right)3.04} \times e^{-\left(\frac{3.0-2.0}{3.6}\right)3.04}$

$R(3.04) = 1 \times e^{-\left(\frac{1}{3.6}\right)3.04}$

$R(3.04) = 1 \times 0.9799 = 0.9799$

In fact, if a preventive maintenance takes place after 2 years, the reliability in two years will achieve 84.62% and in the third year (after preventive maintenance), the reliability will achieve 97.99%, if the replace and repair recover the reliability to the state as good as new.

The highest level of reliability based on preventive maintenance can be demonstrated in the real world when the preventive maintenance schedule is implemented at the proper time, there will no equipment failure and consequently, no corrective maintenance. The absence of failure is a demonstration of high level of reliability or effective preventive maintenance schedule.

The assumption adopted so far in many RAM analysis results, based on software solution available in the market will trigger an equipment failure at some point in the future even performing the preventive maintenance during a scheduled time. That´s happened because the assumption of the reliability must be defined based on the whole interval of time and not only after the preventive maintenance. Therefore, the reliability will be the product of each interval of time where the preventive maintenance took place, having the effect to reduce on time as much as preventive maintenance takes place.

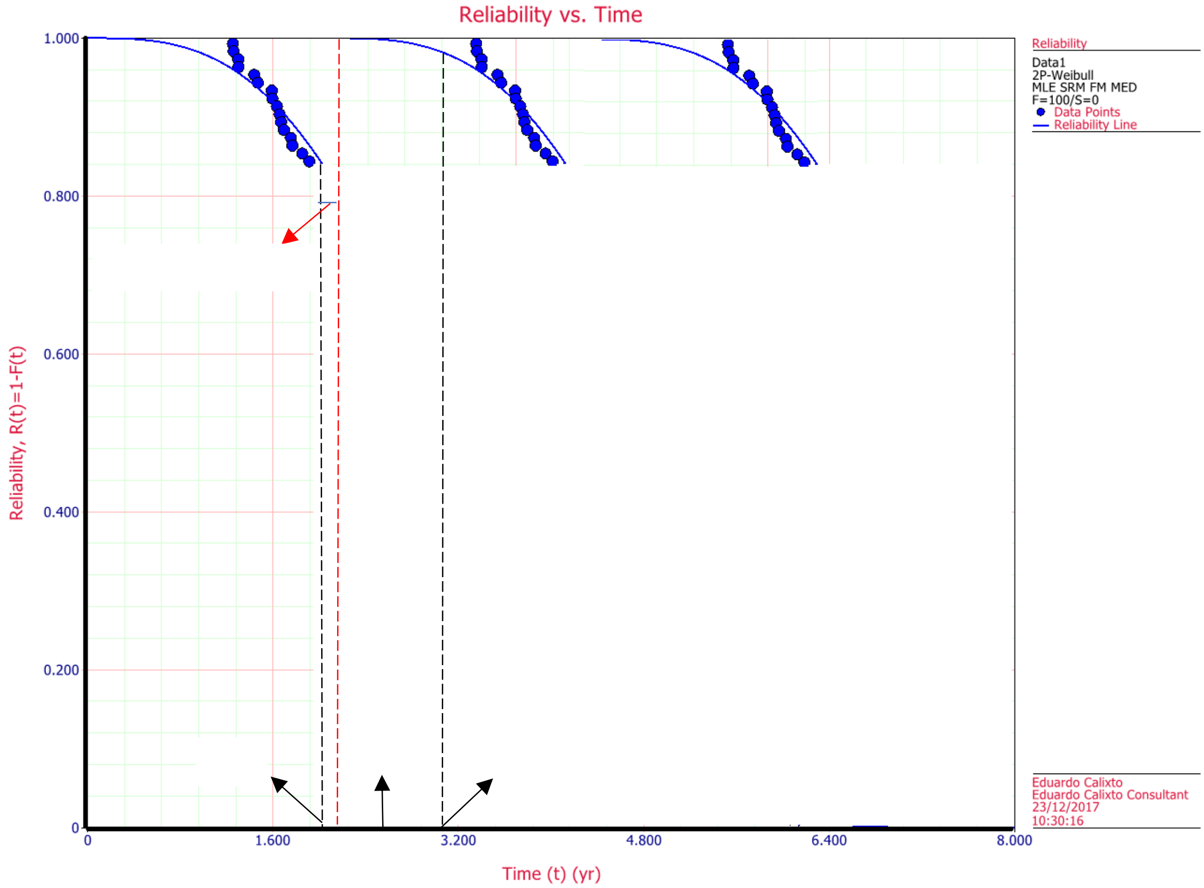


Figure 7 Preventive maintenance interval effect on reliability

The case studies will demonstrate in the item 6 and will show the final effect of preventive maintenance in the reliability result is better in many cases when compared to the maintenance policy run to failure. Even though, as discussed before, such result is pessimistic in terms of reliability because of the assumption the result reliability is the product of reliabilities during the preventive maintenance interval along the defined period of reliability estimation.

The preventive maintenance discussed so far in this item concerns only the schedule maintenance because the software, which run the Monte Carlo Simulation for the RBD model captures only events based on time such as failures time, repair time, inspection time and preventive maintenance time. Even some solution that presents the online monitoring, such option is associated with a schedule period of a lifetime that must be defined.

Therefore, the real effective online monitoring or NDT is not really considered in the RBD modelling. In fact, the NDT needs to have some schedule to be implemented on time and it´s definitely a period between the expected P-F interval, where some degradation is supposed to be detected. In the end, if the degradation process occurs, the schedule maintenance and the real preventive maintenance based on NDT will not have a considerable difference in terms of a range of time. Concerning the Online monitoring, it´s also important to know that not all alarms, which is triggered by the online monitoring system so called PHM confirms a real failure or degradation in the equipment. In the end, every method has some limitation.

6 – Cases Study – The Pantograph RAM analysis

The pantograph RAM analysis follows the methodology defined in the figure 2, which starts with the scope. The following equipment will be considered under the RAM analysis are the following: ***Pantograph Base System*** (Frame; Insulator; Valve Plate); ***Elevation System*** (Cylinder, Spring, Wire Hope, Insulate Hose); ***Pantograph Arm system*** (Power Strap, Shear Frame, Arm, Damper, Guide Rod); ***Collector head System*** (Carbon Strip, End Horn, Bearing, Spring and damping contact).

The Analysis will be taken at component level based on historical data available to predict the pantograph performance index such as operational reliability and reliability. The next step after the scope definition is to collect the reliability and maintainability data. In this case, the LDA was carried out based on historical data on the final result is presented in the table 1.

The next step is to model the Pantograph into RBD and input all reliability and maintainability information in each block which represents an equipment. The Pantograph RDB is demonstrated in figure 6. A part of data collection, on the very beginning was defined the mission profile such as mission time (warranty:2 year), Life cycle (20 years) and Duty cycle (100%).

Table 1 Pantograph reliability and maintainability data

Equipment	Failure (Year)				Repair (Hour)			PM Interval (years)	
	PDF	Parameter			PDF	Parameter		PDF	Time Schedule (TS)
Pantograph Base									
Frame	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		3.7858	2.1055	7.6249		0.5	0.1		7
Insulator	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		3.7357	0.8318	8.2599		0.5	0.1		7
Valve Plate	Weibull 2P	β	η		Normal	μ	∂	Constant	TS
		6.9368	7.5303			0.5	0.1		7
Elevation System									
Cylinder	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		3.7647	4.1892	5.2709		0.5	0.1		5
Spring	Weibull	β	η	γ	Normal	μ	∂	Constant	TS
		3.7562	2.0902	3.6396		0.5	0.1		4
Wire Hope	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		2.5515	2.6484	5.7355		0.5	0.1		5
Insulate Hose	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		2.5258	1.3126	6.8777		0.5	0.1		7
Pantograph Arm									
Power Strap	Weibull	β	η	γ	Normal	μ	∂	Constant	TS
		3.7614	1.2557	2.8822		0.5	0.1		2.5
Shear Frame	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		3.7748	2.5197	6.7565		0.5	0.1		6
Arm	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		2.5395	1.3187	2.8717		0.5	0.1		3
Damper	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		2.5507	1.3238	4.867		0.5	0.1		5
Guide Rod	Weibull 3P	β	η	γ	Normal	μ	∂	Constant	TS
		3.747	2.0855	7.1482		0.5	0.1		7
Coollector head									
Carbon Strip	Weibull	β	η	γ	Normal	μ	∂	Constant	TS
		3.3592	0.285	0.1516		0.5	0.1		0.2
End Horn	Weibull	β	η	γ	Normal	μ	∂	Constant	TS
		2.5397	0.3091	0.641		0.5	0.1		0.5
Bearing	Weibull	β	η	γ	Normal	μ	∂	Constant	TS
		2.5554	0.5303	7.046		0.5	0.1		6
Spring and damping contact	Weibull	β	η	γ	Normal	μ	∂	Constant	TS
		2.541	1.3194	5.8711		0.5	0.1		6

After modelling and input all reliability and maintainability data in each block, including the preventive maintenance tasks defined in the RCM, it’s time to run the Monte Carlo Simulation considering the pantograph system profile. Therefore, the results are the following:

- Operational availability in 2 years: 99.93%
- Reliability in 2 years: 99.95%
- Expected number of failures: 0.047
- Total life cycle cost (maintenance) in 2 years: £2949.26

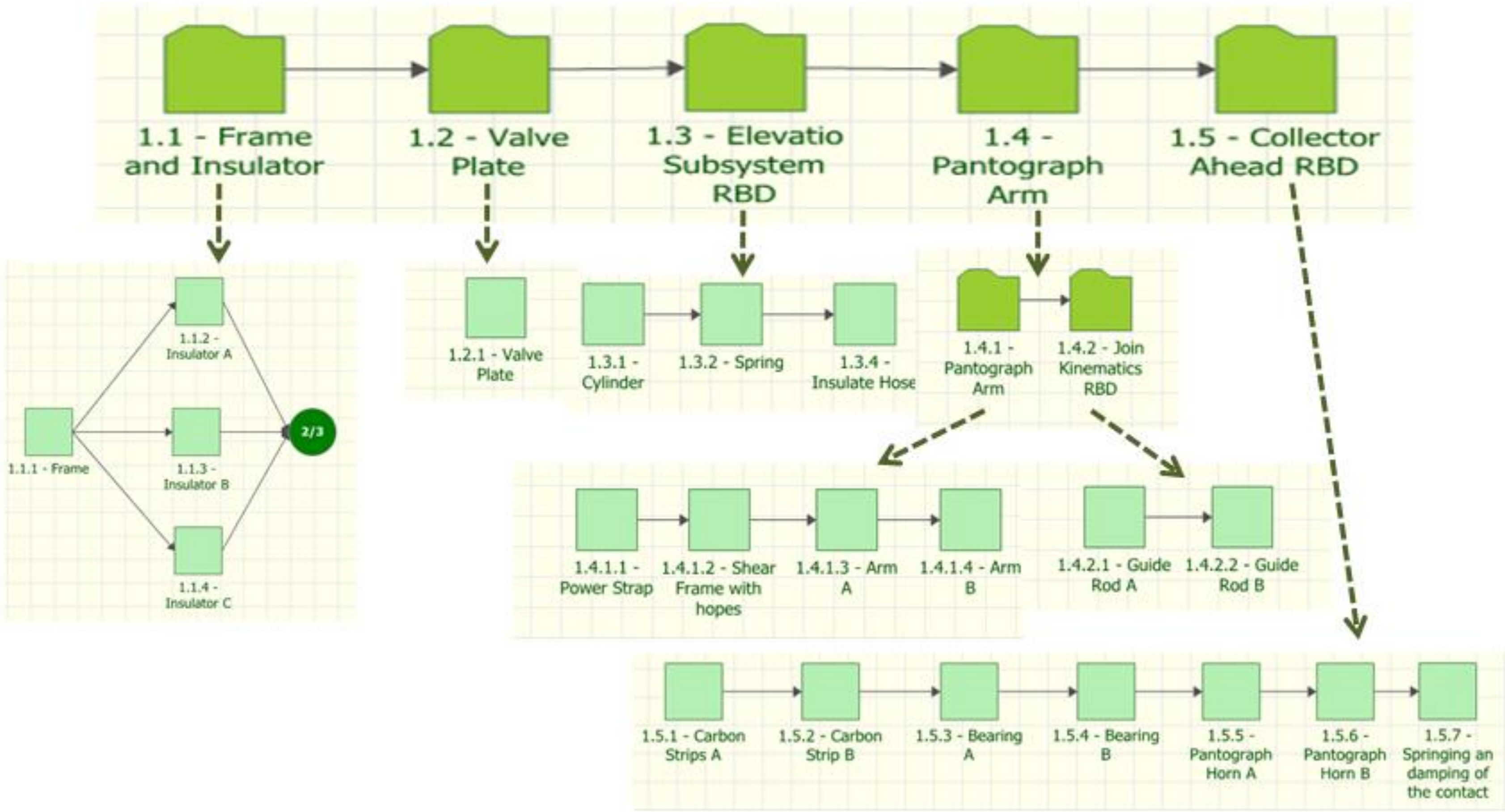


Figure 6 Pantograph RBD (Top Down configuration)

The results show a high performance achieved, which is enabled by the implementation of Preventive maintenance schedule for the Carbon strips (every 0.2 years) and Pantograph Horns (0.5 years), which avoid the failures of such equipment a keep the reliability high as shows the figure 8.

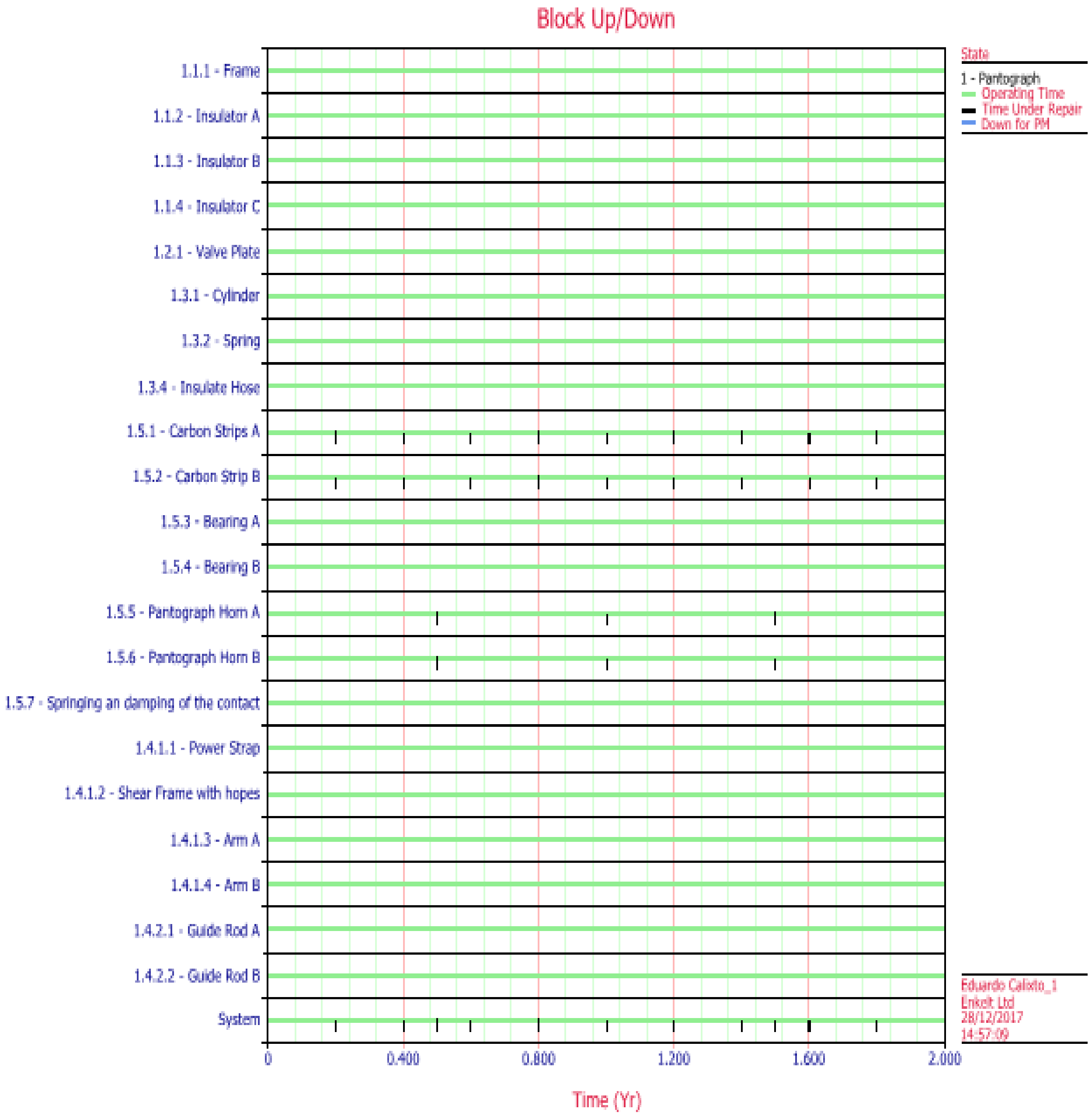


Figure 8 Pantograph Simulation result (Blocks up/down 2 years)

After the simulation, the next step is to assess the most critical equipment which impact on the pantograph performance. Since the failures are avoided by preventive maintenance, the impact of operational availability caused by the preventive maintenance downtime can be assessed by the Downtime Critical Index (DTCI). The figure 8 shows the carbon strip and the pantograph horn as the most critical equipment concerning the downtime impact caused by the preventive maintenance. In order to have a better conclusion, the simulation for the criticality analysis was carried out to the whole lifetime cycle (20 years).

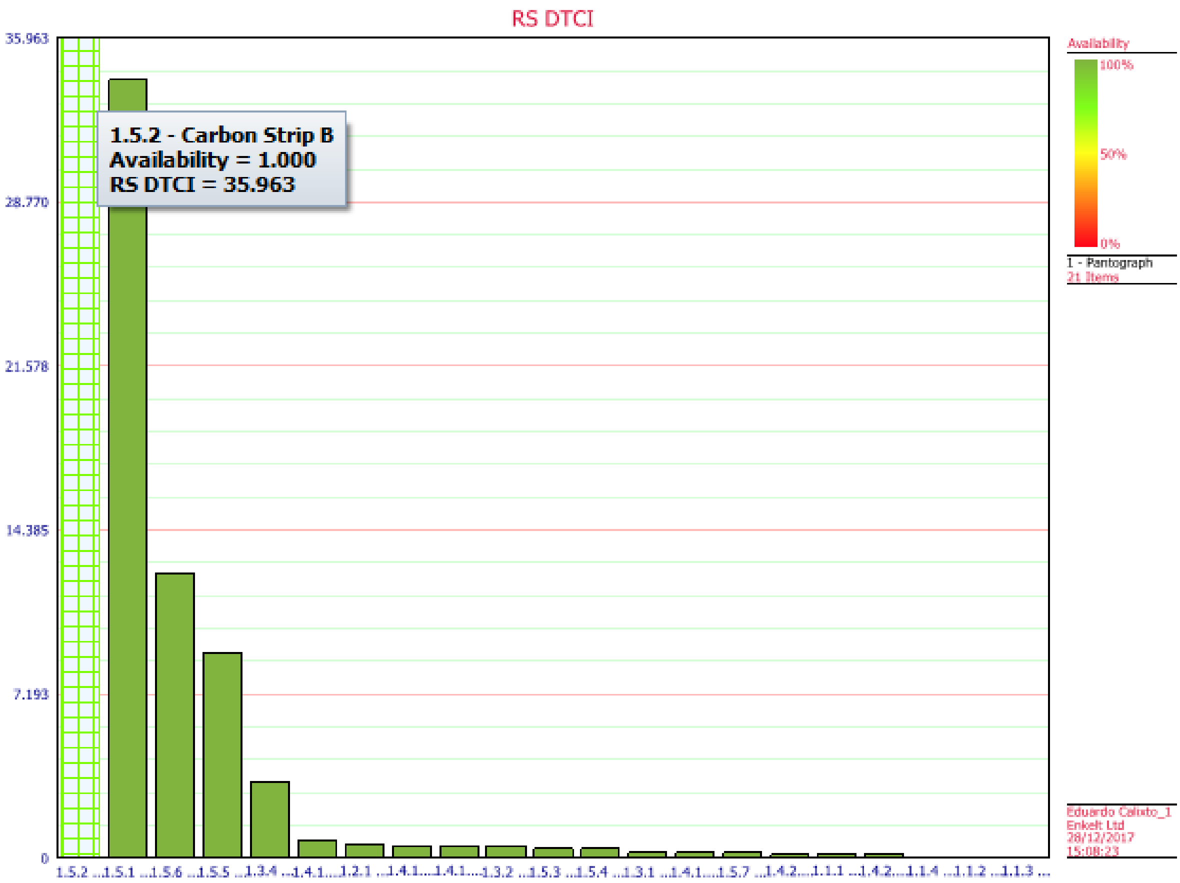


Figure 9 Pantograph criticality analysis (DTCI 20 years)

Based on the figure 9, if it´s necessary to improve the Pantograph performance (Operational availability), the equipment to be improved are the carbon strips and he pantographs horns. Therefore, if necessary, these equipment reliability needs to be improved in order to reduce the downtime related to the number of preventive maintenance. Despite of the environmental condition, such equipment reliability cannot be improved. Therefore, such performance achieved by the pantograph system is a good performance. The final step is the sensitivity analysis, which may assess the pantograph vulnerabilities such as lack of spare parts, impact of other external system and events as well as the Life cycle cost assessment.

In order to compare the life cycle cost concerning preventive maintenance and corrective maintenance, the simulation was carried out considering these two scenarios. The figure 10 shows the both results. Despite of the high reliability achieved based on the preventive maintenance, implementation, life cycle cost of the scenario with preventive maintenance (£2949.26) is higher than the other one without preventive maintenance (£2139.50). In addition, the operational availability in the scenario with preventive maintenance (99.94% in 2 years) is lower than the other one without preventive maintenance (9996% in two years). Such results require a deeper assessment of the maintainability as well as the optimization of the preventive maintenance schedule to enable a better operational availability and lower life cycle cost. Such type of analysis is part of the integrated logistics support which will be discussed in chapter 8.

System Overview (With PM)	
General	
Mean Availability (All Events):	0.99939
Std Deviation (Mean Availability):	0.000026
Mean Availability (w/o PM, OC & Inspection):	0.999999
Point Availability (All Events) at 17520:	1
Reliability(17520):	0.955
Expected Number of Failures:	0.047
Std Deviation (Number of Failures):	0.220997
MTTFF (Hr):	380755.8565
MTBF (Total Time) (Hr):	372765.9574
MTBF (Uptime) (Hr):	372538.391
MTBE (Total Time) (Hr):	831.829836
MTBE (Uptime) (Hr):	831.32202
System Uptime/Downtime	
Uptime (Hr):	17509.30438
CM Downtime (Hr):	0.02302
Inspection Downtime (Hr):	0
PM Downtime (Hr):	10.672601
OC Downtime (Hr):	0
Waiting Downtime (Hr):	0
Total Downtime (Hr):	10.695621
System Downing Events	
Number of Failures:	0.047
Number of CMs:	0.047
Number of Inspections:	0
Number of PMs:	21.015
Number of OCs:	0
Number of OFF Events by Trigger:	0
Total Events:	21.062
Costs	
Total Costs:	£2,949.26

System Overview (without PM)	
General	
Mean Availability (All Events):	0.999642
Std Deviation (Mean Availability):	0.000033
Mean Availability (w/o PM, OC & Inspection):	0.999642
Point Availability (All Events) at 17520:	1
Reliability(17520):	0
Expected Number of Failures:	12.56
Std Deviation (Number of Failures):	0.91062
MTTFF (Hr):	3148.755
MTBF (Total Time) (Hr):	1394.904
MTBF (Uptime) (Hr):	1394.405
MTBE (Total Time) (Hr):	1394.904
MTBE (Uptime) (Hr):	1394.405
System Uptime/Downtime	
Uptime (Hr):	17513.72
CM Downtime (Hr):	6.279401
Inspection Downtime (Hr):	0
PM Downtime (Hr):	0
OC Downtime (Hr):	0
Waiting Downtime (Hr):	0
Total Downtime (Hr):	6.279401
System Downing Events	
Number of Failures:	12.56
Number of CMs:	12.56
Number of Inspections:	0
Number of PMs:	0
Number of OCs:	0
Number of OFF Events by Trigger:	0
Total Events:	12.56
Costs	
Total Costs:	£2,139.50

Figure 10: Pantograph Simulation (sensitivity analysis 2 years)

6 – Conclusions

The paper achieved successfully its objective which was to demonstrate the RAM methodology concept and application. Despite the complexity of the statistic concepts as part of the LDA, as well as the steps of the RAM analysis methodology that must be implemented, such methodology has the potential to support the railway asset development during the concept and design phase and support decision during the operational phase when an asset does not achieve it performance index.
The Pantograph case study demonstrated the step by step of the ram methodology implementation concerning the quantitative reliability and maintainability data as input to performance prediction. In addition, the preventive maintenance and the life cycle cost were also considered to demonstrate the tradeoff between the corrective and preventive maintenance.
The detailed RAM analysis approach is described in the book RAMS and LCC engineering: Analysis, Modelling and Optimization including the description of the effect of maintenance in reliability (the kijima factor I and II), the tradeoff analysis between redundancy and reliability target achievement, the detailed information concerning the criticality index that defines the bad actors that affect the system operational availability and reliability target and the reliability allocation. In addition, the other case studies applied to brake and bogie system are presented in the book.