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LIFE CYCLE MANAGEMENT AND RELIABLITY ANALYSIS OF CONTROLS HARDWARE USING OPERATIONAL DATA FROM EAM

E. Fortescue†, I. Kozsar, CERN, Geneva, Switzerland
V. Schramm, Institute of Machine Components, University of Stuttgart, Germany

Abstract

The use of operational data from Enterprise Asset Management (EAM) systems has become an increasingly popular approach for conducting reliability analysis of industrial equipment. This paper presents a case study of how EAM data was used to analyse the reliability of CERN's standard controls hardware, deployed and maintained by the Controls Electronics and Mechatronics (CEM) group. The first part of the study involved the extraction, treatment and analysis of state-transition data to detect failures. The analysis was conducted using statistical methods, including failure-rate analysis and time to failure analysis to identify trends in equipment performance and plan for future obsolescence, upgrades and replacement strategies. The results of the analysis are available via a dynamic online dashboard. The second part of the study considers Front-End computers as repairable systems, composed of the previously studied non-repairable modules. The faults were recorded and analysed using the Accelerator Fault Tracking (AFT) system. The study brought to light the need for high quality data, which led to improvements in the data recording process and refinement of the infrastructure team's workflow. In the future, reliability analysis will become even more critical for ensuring the cost-effective and efficient operation of controls systems for accelerators. This study demonstrates the potential of EAM operational data to provide valuable insights into equipment reliability and inform decision-making for repairable and non-repairable systems.

INTRODUCTION

CEM's Infrastructure (IN) section is responsible for the life-cycle management of a very large collection of hardware components for the Front-End Computers (FECs) distributed across the entire CERN accelerator complex. Planning for replacement and upgrades has become a real challenge. Therefore, having readily available reliability metrics such as the Mean Time To Failure (MTTF), or statistics to determine whether the failure rate is increasing for a given equipment type, known as a part in asset management terminology, can significantly aid strategic decision-making.

Since 2005, instigated by the need for industrial-scale asset management during the installation of the controls hardware in the LHC, the CEM-IN section has invested heavily in using CERN's Enterprise Asset Management (EAM) system [1], to follow operational equipment through its' life cycle. The EAM system provides many functionalities including history tracking, user-defined state machines, spare part and store management, and user reporting.

Assets are registered in the EAM system for instances of any part that need to be individually tracked, such as electronic boards, chassis, power supplies, fans, etc. The corresponding barcodes, or QR codes, are attached to the physical equipment upon reception at CERN. All movements and events affecting the asset are recorded in the EAM system, such as installation in a new position, attachment to, or detachment from a parent asset, return or issue from a store or changes in asset status e.g. Installed, In Repair, Out of Service etc.

USE OF STATE-TRANSITION DATA

The Infrastructure section registered and traced an increasing number of electronic assets in the EAM system over a period of more than 15 years. CEM-IN currently manage approximately 50,000 operational assets and 300 distinct parts, and in 2021, it was considered that sufficient historical data was present in EAM to be able to attempt a rudimentary reliability analysis.

The first initiative was to extract, process and analyse the state-transition data to detect failures in the electronic modules and generate reliability statistics per part.

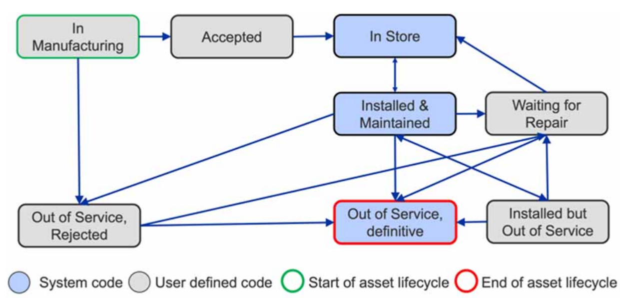

Figure 1: Custom state machine for CEM-IN assets.

Figure 1 shows the custom state machine applied by the EAM system to the CEM-IN assets between 2005 and 2021. Whenever an asset changes from one state to another, the state-transition is recorded and timestamped in the asset's history. A failure, as defined in this context, was deemed to have occurred on the date that an asset's state passed directly from "Installed and Maintained" to "Waiting for Repair". By querying this basic state-transition data, it is straightforward to determine how many failures occur per calendar year for a given type of electronic module.

† Eve.Fortescue@cern.ch

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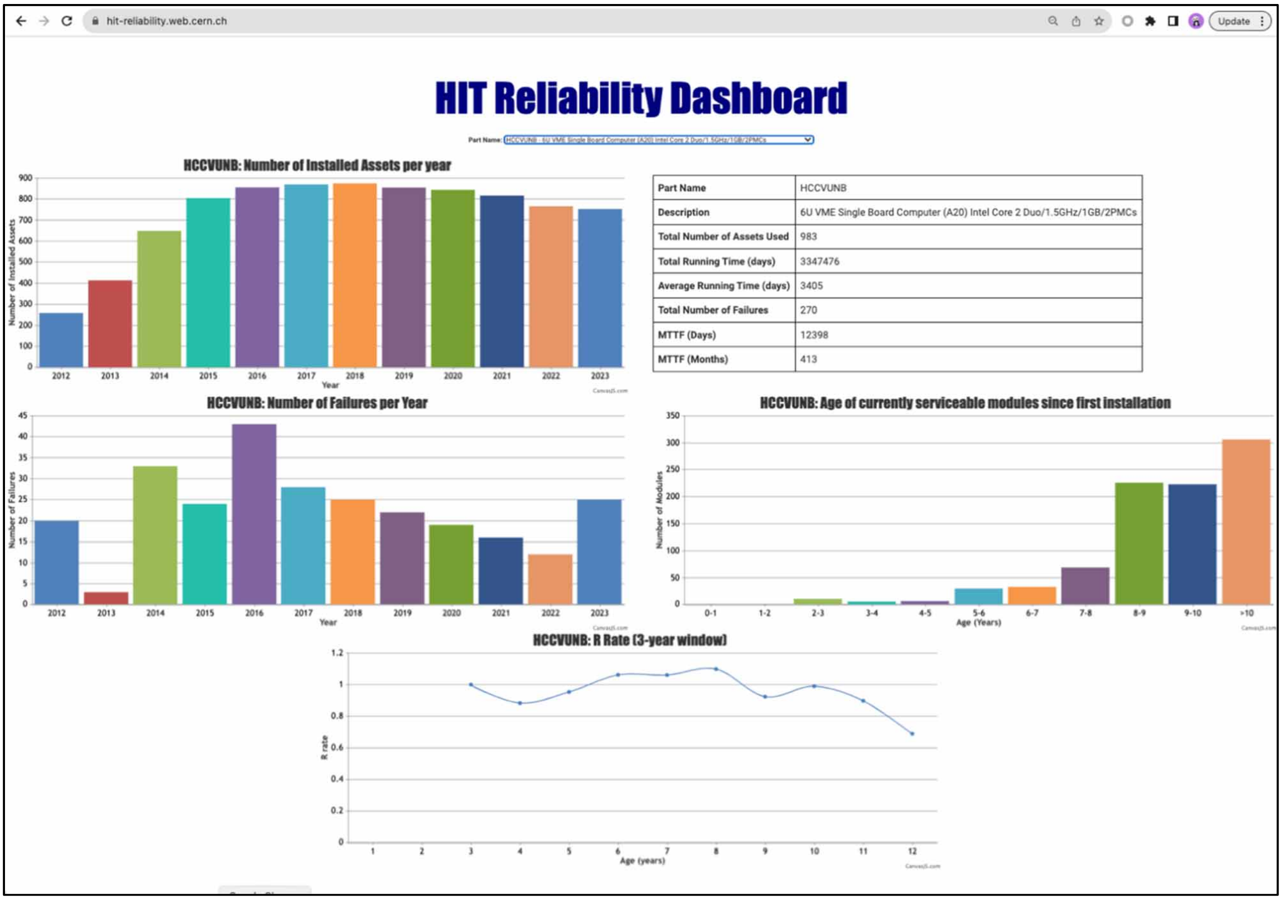

Figure 2: The HIT Reliability Dashboard.

However, the electronic assets were initially installed at different points in time and may have been dismantled, returned to the store and re-installed several times throughout their lifetime, before failing. Therefore, in order to obtain statistics that would be more useful in predicting the end-of-life (EOL) of a part, it was necessary to perform more complex queries on the state-transition data. The initial installation dates for each asset of a given part were normalised to a common t_0 and the installation periods for each asset calculated and packed to appear continuous. The Time To Failure (TTF) was then calculated with respect to the operational age. The individual asset's running times were summed in order to produce the total running time per part, and subsequently, the Mean Time To Failure (MTTF) was calculated for each part, using the formula shown in Eq. (1).

$$MTTF = \frac{Total\ running\ time\ of\ all\ assets\ of\ a\ given\ part}{Total\ number\ of\ failures\ of\ a\ given\ part} \quad (1)$$

Finally, an R-rate calculation, Eq. (2), was applied to determine the evolution of failure rate with operational age. The R-rate, R_x, is the rate of failure in the last x years, divided by the failure rate since time t_0. If the value of R_x for a given part is equal to or less than one, then the failure rate's behaviour is constant or decreasing. However, if it is greater than one, the failure rate is increasing and may merit further monitoring and investigation to ascertain whether a part is starting to reach its End of Life (EOL) after a specific number of years in operation. The x-year time-window smooths the curve, compensating for the low data quality and the non-continuous operation of the machines.

$$R_x = \frac{Failure\ rate\ in\ last\ x\ year}{Failure\ rate\ since\ t_0} \quad (2)$$

ONLINE DASHBOARD

In order to exploit the calculated reliability data and make it available to all members of the team, a dynamic, online dashboard was developed. The raw state-transition data for all assets was obtained from EAM in a database view. A set of Oracle database views querying the transition data were then built to aggregate, filter and group the data, as described above. The online HIT (Hardware Infrastructure Team) Reliability Dashboard was developed using PHP and Ajax technologies, the ChartJS [2] charting library and is hosted on the standard centralised web servers provided at CERN.

The dashboard (Fig. 2), allows a user to generate and visualise the latest reliability metrics of any CEM-IN part registered in the EAM, including:

- Graph of number of assets in operation per year.
- Graph of number of failures per calendar year.
- Total number of assets
- Total number of failures.

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- Total running time per part.
- Average running time per part
- MTTF in days and months.
- Graph of age of modules since first installation
- Graph of R-rate, showing evolution of failure rate with component age.

ASSUMPTIONS & LIMITATIONS

In this case, the electronic modules were considered to be non-repairable systems and only the time to the first repair was taken into account, regardless of whether the module was subsequently repaired and put back into service. Furthermore, for the MTTF, a constant failure rate was assumed. All equipment types were treated in the same way in this study and no difference in methodology was applied between low-stress and high-stress components. High-stress components such as power supplies do experience stress-related failure mechanisms. However, no fault codes or failure mechanisms were recorded in the historical data, nor was a sub-component root-cause analysis available for the modules. Finally, as the controls hardware runs almost constantly, the calculation of equipment age did not differentiate between operation and shutdown periods.

FECS AS REPAIRABLE SYSTEMS

The second part of the CEM reliability study, started in 2022, considers FECs as repairable systems, composed of the previously studied non-repairable modules[3]. The failures were recorded as "faults" and analysed using CERN's Accelerator Fault Tracking (AFT) system [4].

Failures in CEM FECs are again detected from the EAM state-transition data, when an asset that is a sub-component of an installed FEC is detached from its assembly and passes into the "Waiting for Repair" status. Automatic email notifications are configured to report on all assets passing into this status in the previous week. These potential faults are cross-referenced with JIRA support issues to confirm that an intervention had taken place.

Confirmed failures were registered manually in AFT, with the FEC declared as the "Faulty Element" and the equipment type and the serial number of the asset recorded in order to show the sub-component of the FEC that failed e.g. the fan, power supply, CPU etc. The sub-component equipment types were classified by hardware platform, with a view to generating statistics relating to the reliability of each technology. The downtime of the FEC, from the moment of failure to restart was obtained from the Controls Survey and Monitoring System (COSMOS)[5], via the Icinga web interface, and added to the AFT fault. The fault was declared as "blocking" or "non-blocking" depending on whether the FEC was an operational or development machine, and whether the intervention took place during machine operation or a shutdown period. All CEM hardware faults, since the start of the LHC's third run, were retroactively added to AFT.

The main advantage of using AFT is that CEM benefit from the in-built statistics and drill-down charting capabilities. Some of the most useful statistics generated by AFT for CEM include:

- Bar charts of downtime per platform, equipment type or FEC (Fig. 3).
- Bar charts of number of faults per platform, equipment type or FEC.
- Bubble plots of fault count vs duration, per platform, equipment type or FEC. (Fig. 4)
- Donut charts of fault time distribution by platform and FEC.
- Bar/Line graph of weekly fault counts and duration (Fig. 5).

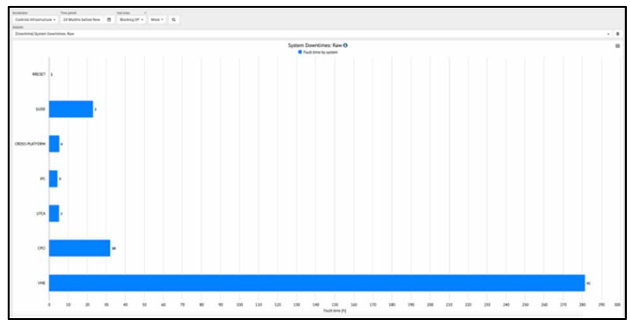

Figure 3: Barchart of downtime per platform.

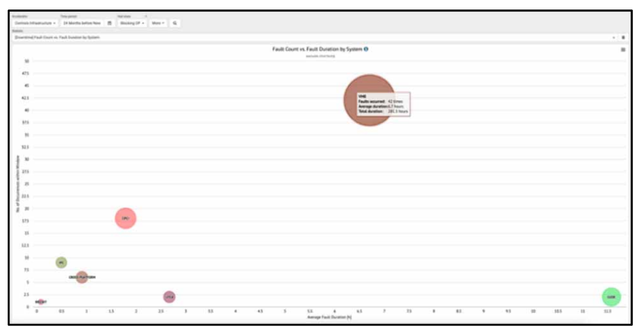

Figure 4: Bubble plot of fault count vs fault duration per platform.

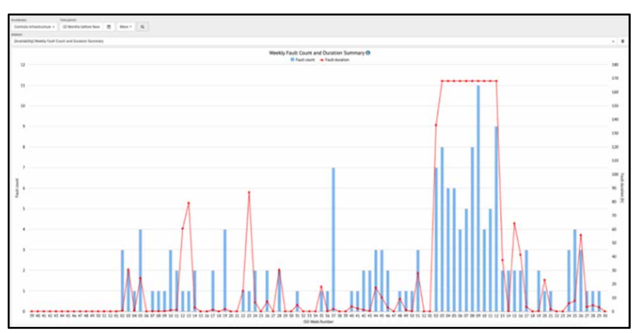

Figure 5: Bar & line graph of weekly fault count and duration.

These charts allow CEM to easily identify the platforms which are most problematic, the parts that report the highest number of failures, or take the longest to repair, and any particular FEC that may suffer from repeated problems. This information is extremely valuable and together with the information from the HIT reliability dashboard, can be

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used to plan for consolidation or replacement of individual FECs, platforms or equipment types, improve the efficiency of interventions and with the improvements described in the next chapter, potentially pre-empt EOL failure before it occurs and causes significant downtime.

It can also be used to evaluate the timing of consolidation plans. For example, in 2022 the reliability statistics were consulted to evaluate whether the MEN-A20 CPUs needed to be replaced in LS3. The current evidence showed that the failure rate was low and not increasing, thus suggesting a smooth replacement of the failed units instead of a massive consolidation campaign that would have been challenging in terms of resources and budget to allocate.

Weibull analyses could also be performed with the FEC level as a starting point to trigger and perform a Root Cause Analysis and determine individual EOL failure mechanisms. However, AFT does not currently provide such functionality and extracted data would have to be evaluated using a specific tool.

DATA QUALITY & IMPROVEMENTS

In order to improve the quality of the operational data, discussions were undertaken with the group's reliability design experts to consider new data that could be collected. One suggestion is to define failure codes in EAM to record precisely why an asset failed. If this was to be done correctly, each of the 300 parts in the hardware catalogue would require a custom list of failure codes. Furthermore, this would require a significant resource investment to determine the precise failure mode, cause and subsequently mechanism of a failing asset, which may not be possible for every observed failure. Unfortunately, for purchased parts we do not have a Bill of Materials (BOM) with which to identify sub-components that could fail. For parts that are designed in-house, it is preferable to build in reliability from the design stage and the effort required to retrofit the process to existing hardware would be unwarranted.

In the future it might be powerful to set an threshold on the R-Rate for each part, which automatically generates alarms when the threshold is exceeded.

It was also clear that the state machine had several limitations, which affected the quality of the statistics that were being produced. Firstly, before 2021, all dismantled equipment passed by default into the status "Waiting for repair" for testing and cleaning, even if no failure had occurred. Therefore, very early in the study, a new status "Returned from installation" was introduced in order to differentiate dismantled assets from those that had been replaced due to operational faults. Furthermore, when entering fault data into AFT, it was noticed that there is often a delay of up to a few months between an operational problem being reported, triggering an asset exchange, and the asset being potentially repaired after tests. Upon testing, it is also possible to discover that an asset is not faulty. Consequently, the EAM state machine was completely redesigned to model more closely the life cycle of the assets, better constrain the possible state-transitions and ultimately generate more accurate reliability statistics (Fig. 6).

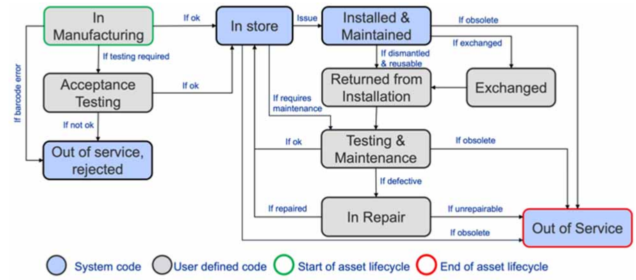

Figure 6: New EAM state machine for CEM-IN assets.

With this new workflow, registering faults in AFT becomes a two-step process. At the moment of the intervention, or when an asset passes through the new state "exchanged", the fault is registered along with the downtime and details of the faulty element, but the fault remains unvalidated. The asset is then tested and only if it is faulty, does it pass to the status "In repair" in EAM. At this point the fault can be validated in AFT. If during testing, the asset is found not to be faulty, the unvalidated fault record is deleted from AFT and the asset is returned to the store in EAM. Automatic weekly reports are configured to detect the relevant state-transitions in EAM and the asset manager is notified so that AFT can be updated.

CONCLUSION

The HIT reliability dashboard has been in production since September 2021 and the AFT data is being collected since October 2022. Both systems are regularly consulted to help inform decision-making. The study has demonstrated the potential of EAM operational data to provide valuable insights into equipment reliability, but highlighted the necessity for high-quality data in order to be able to leverage it for reliability analysis. This feedback led to further improvements and refinement of the CEM group's EAM custom state machine. It is clear that reliability analysis is likely to become even more critical for ensuring the cost-effective and efficient operation of control systems for accelerators in the future.

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