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DEVELOPMENT OF AN ALGORITHM TO AUTOMATE FAULT ANALYSIS IN THE AUTOMOTIVE INDUSTRY.

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SUMMARY

Industry tries to control all the variables involved in its processes in order to prevent its most varied products from deviating from the conformity normally recommended by the quality teams. When a defect occurs in a given product, time, manpower and, above all, money are often wasted, because a production line that stops is much more expensive than one that runs without defects. The aim of this research is to develop an algorithm capable of automating the analysis of electrical faults in a vehicle. To this end, the results of a survey of the faults repaired by the electrical systems analysis team on a production line in a premium car factory in the interior of the state of Rio de Janeiro over a three-month period were taken into account, and the four most recurrent faults with the greatest impact on the factory's quality indicators were selected from a list of the "top ten". Once the unanalysed defects had been identified, an algorithm was developed to analyse each of them in detail with their respective outputs. Automating this analysis saves time because instead of searching for possible causes, as technicians do, this algorithm guides the user directly to the most likely cause. At the end of this application, the result is a saving of time in these analyses, which can last from hours to days and have an impact not only on quality indicators, but also on efficiency and the delivery of vehicles to customers.

Keywords: Production line; Automation; Failure analysis; Algorithms

1. INTRODUCTION

In the contemporary business environment, industries are compelled to attain a level of quality in their products that is commensurate with the expectations of a progressively discerning market. The automotive industry, in particular, faces considerable challenges in a market that is becoming more competitive every year with the entry of several Asian brands, which in themselves bring several innovations to a public eager for technological innovations.

The integration of innovative technologies into complex products such as automobiles necessitates significant efforts from manufacturers, particularly in the domains of development and validation. This process is then disseminated throughout the assembly line.

Concurrently, production lines must be adapted to support the integration of these advanced technologies, necessitating the introduction of novel manufacturing methodologies and the application of technical innovations within the production process.

In order to facilitate End-of-Life (EOL) activities in manufacturing that extend beyond the scope of vehicle assembly, this research proposes an algorithm that contributes to the automation of analysing electrical faults in vehicles. The implementation of this algorithm is expected to facilitate the analysis of potential causes by providing a framework for the identification of probable problem sources. This will enable repair technicians to investigate faults more efficiently. It is anticipated that this approach will result in significant time and cost savings, as it will eliminate the need for hypotheses and component tests, thereby preventing potential component burnouts during the repair process.

Industrial processes require highly complex applications, in terms of case studies that indicate solutions to problems of poor quality in manufactured items, or even production stoppages caused by equipment failures. The integration of automation systems with Internet of Things (IoT) solutions allows for the acquisition of large volumes of information, which often goes unanalysed due to a lack of knowledge (Peng, 2012).

Some failures, already commonplace, have a high rate of repeatability, and because of this, performance indicators are greatly affected, leading to poor results for the entire plant (Papadopoulos, Parker and Grante, 2001). To improve these indicators and ensure better analysis and response times, the research proposes the development of algorithms (Fuping, Yiran and Guoqing, 2021) to automate analyses and make them more effective and faster, compared to established problem analysis methods such as FMEA (Cristea and Constantinescu, 2017).

The research, conducted at a vehicle manufacturing facility, utilized various quality and efficiency indicators, including a parameter designated as DPU (Defects Per Unit). This metric is persistently influenced by electrical fault issues. This indicator presents a top ten of faults that are constant and affect other internal processes and even delivery to the sales department.

The study commences with the observation of four representative faults. The company has its own process for parameterizing and configuring electronic modules, which are divided into workstations along the production line. The results obtained at these stations are then tallied at the conclusion of the process, thus providing a comprehensive measurement of the efficiency of the production line as a whole. A procedure has been developed based on each of the four most frequent faults in order to help resolve the root cause of the fault and reduce the vehicle's repair time, which is also measured and taken into account in the industrial plant's daily objectives.

In this research, we have a vehicle factory that has production line efficiency indicators whose results, measured over a three-month period, tend to fall due to electrical assembly problems. It is imperative that these issues are addressed within the assembly stations without being transferred to subsequent stations.

It has been observed that certain failures, which are already prevalent, exhibit a high degree of reproducibility. This has a significant impact on performance indicators, resulting in suboptimal outcomes for the entire plant (Wei, Feng and Hong, 2017). In order to enhance these indicators and ensure a superior analysis and response time, the research proposes the development of algorithms (Li, Frey and Gauterin, 2024) to automate analyses and make them more effective and faster in comparison to established problem analysis methods such as FMEA (Han and Zhang, 2013).

2. AUTOMOTIVE PRODUCTION

The automotive production process as we know it today has its origins in the production line model devised by Henry Ford in the early 20th century. This model was designed with the aim of increasing productivity and reducing production costs.

Basically, the assembly model proposed by Ford was a conveyor belt that carried the product to be worked on by the worker, who remained stationary at their post waiting for demand. Over time, other models emerged and further improved on this first one. One of the most widespread models in this field is the Toyota model, a Japanese industrial production model known for its adoption of the just-in-time system, which values meeting demand and avoiding inventory.

Manufacturing processes have also evolved to keep pace with technological advances, such as when embedded electronics began to gain more and more space in the automotive industry due to compliance with emission levels (Juez et al., 2017), and this change brought new processes and new tools for assembling vehicles on the production line, which now had diagnostic systems that made it possible to diagnose product faults. Something unthinkable until then without the application of technology.

Nevertheless, the level of automation on production lines has also increased. Tasks that were previously strenuous or required a certain degree of accuracy from workers have been replaced by robots, and module programming processes have begun to appear on the lines. What was previously solved with simple tools and a little skill has been replaced by computers at the end of the line performing programming and diagnostics on vehicles.

It is also clear that faults have become more complex, with many components joining mechanical systems and IoT, which is increasingly present in industry, also present in vehicles that are increasingly connected and dependent on more advanced equipment on the production line. With vehicle electrification increasingly in vogue, once again we are facing an evolution of processes to meet new product requirements.

3. METHODOLOGY

The research was conducted at a premium SUV manufacturing facility situated in the interior of the state of Rio de Janeiro. The results of the analysis of electrical faults within the three-month period of January, February and March 2024 were considered. The data was extracted from a results platform that collects information directly from the production line equipment via its own server.

The data is consolidated into a central company pool, from which reports are generated daily, weekly, or monthly, providing detailed insights into workstation efficiency. The faults read from the CAN network (Liwei et al., 2014) of the modules by the parameterisation equipment are collected over a period of one day, and for the research, four faults were considered from a list of the ten faults with the most occurrences and which, in turn, most affected the quality indicators.

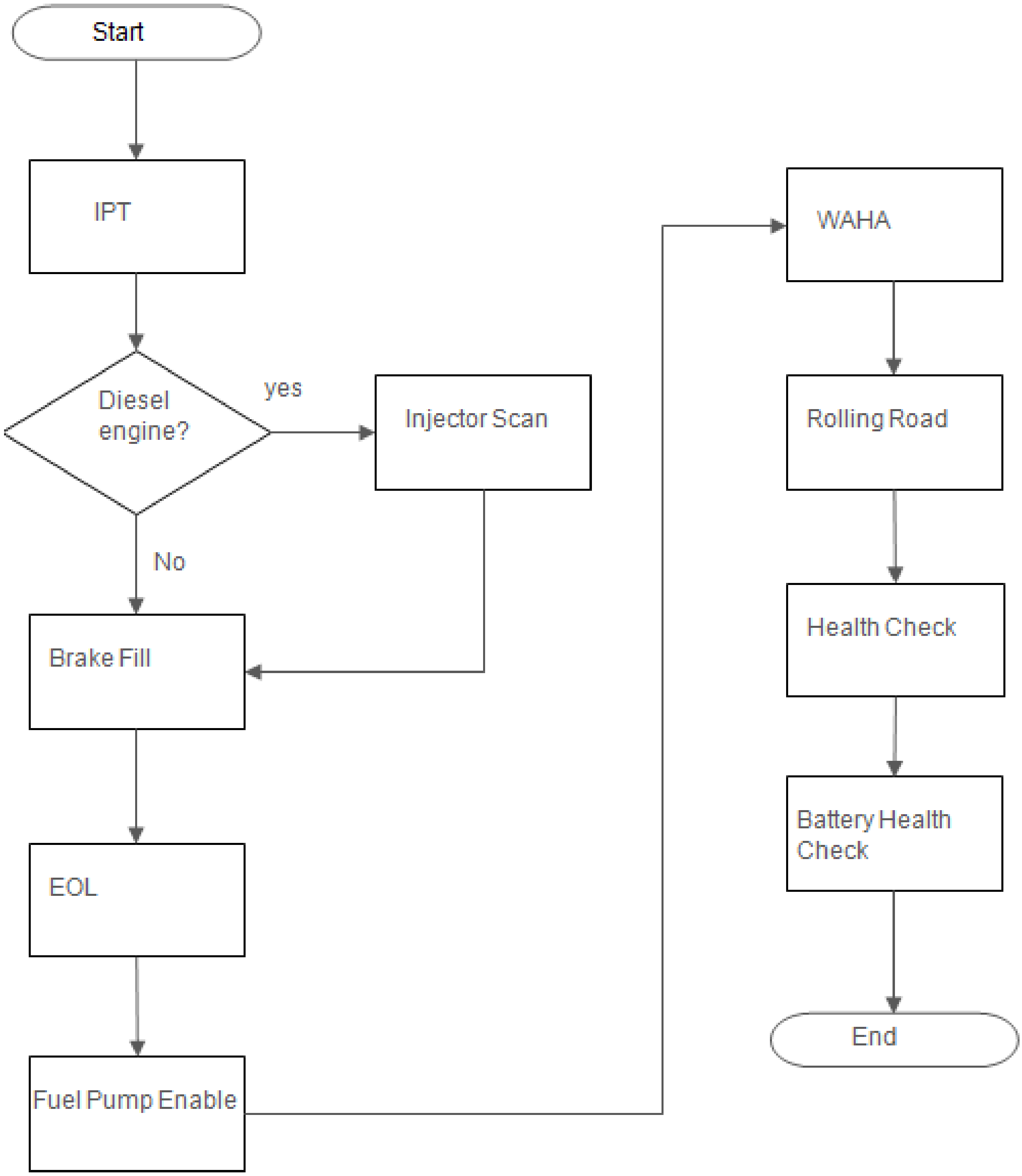
3.1 THE PROCESS OF CONFIGURING THE ELECTRICAL MODULES ON THE PRODUCTION LINE

The configuration of the electrical modules on the production line is a multifaceted process that is subject to investigation. The process is subdivided into a series of stages along the production line, with the intention that an electrical process is concomitant with each stage of vehicle assembly. The process is subdivided into the following phases:

- IPT (in-process testing) is the stage at which the software is downloaded and the modules on the centre console and dashboard are parameterised.
- Injector Scan: This step is only carried out when the vehicle has a diesel engine, as the injector nozzles are coded and their code needs to be scanned to be made available in the system.
- The brake fill step entails the replenishment of the brake fluid, air conditioning gas, and engine cooling system reservoirs. The values are then read by the vehicle's sensors and once filled, the fluid is released to the next station.
- The End of Line (EOL) represents the culmination of the assembly line, wherein all modules are already assembled, and software parameterisation and fault testing can be conducted.
- The fuel pump is then enabled at this stage. It is imperative to ensure that all faults have been rectified and no further risks are present before the vehicle can be started.
- WAHA (Wheel Alignment and Headlamp Adjust) is the stage at which the alignment of the wheels and headlamps is conducted.
- RR (Rolling Road) - This is a dynamic test conducted within a cabin that replicates a driving condition of 80 kilometres per hour, with all on-board systems operational.
- The Health Check station is the stage of the process where the vehicle's entire electrical and electronic systems are subjected to rigorous scrutiny to identify any potential faults.
- The final stage of the process is the Battery Health Check, at which the voltage of the battery is measured. Once this has been completed, the vehicle is ready to be delivered to the yard.

The process is delineated in Figure 1.

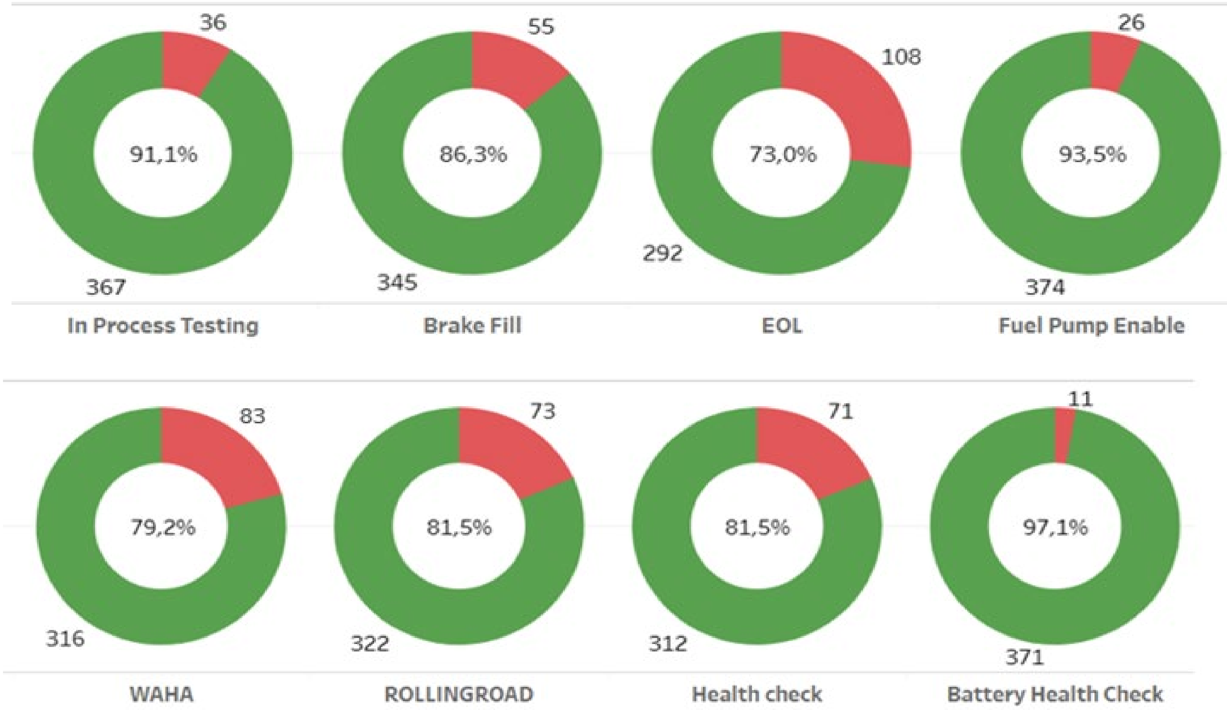
Figure 1 | Flow chart of the electrical process of the company.



3.2 Selection of faults to be analysed

The faults studied in the study come from an internal quality indicator that shows daily, weekly, monthly or periodic results. In this research, the period considered was the first quarter of 2024, comprising the months of January, February and March, where the indicator shows a significant frequency of faults relating to the modules responsible for controlling the door lock and windows (DRDM), opening and locking the boot (RGTM), telematics control (TCU) and problems with the cooling circuit filling system (Enzi and Khan, 2022). Figure 2 shows the results per station over the period considered.

Figure 2 | Effectiveness indicator per electrical parameterisation station



As demonstrated by the indicators presented above, an extraction revealed the most prevalent faults and their frequency over the specified period. The results of this extraction are presented in Tables 1 to 8.

Table 1 | Extraction of the history of failures in the period for In Process Testing.

Process	Index	Test Fix	DTC	DTC Description	Total cases
In Process Testing	1	IPCB SWDL	S58963	GGDS ProtocolAccess - Transport DOIP _UNKNOWN_ Target_ADDR	18
	2	IPCB Prog mode	S58963	GGDS ProtocolAccess - Transport DOIP _UNKNOWN_ Target_ADDR	18
	3	IPCB Part Number	S118963	VBF_SWDL ProtocolAccess-Transport DOIP_UNKNOWN_Target_ADDR	18
	4	IPCB HW Check	S58963	GGDS ProtocolAccess - Transport DOIP _UNKNOWN_ Target_ADDR	18
	5	Manual Checks	V3637	High Mounted Stop Lamp fault	3
	6	ICCM Initialised check	V4166	Not Initalised	3
	7	AAM SWDL	S58963	GGDS ProtocolAccess - Transport DOIP _UNKNOWN_ Target_ADDR	3
	8	AAM Prog Mode	S58963	GGDS ProtocolAccess - Transport DOIP _UNKNOWN_ Target_ADDR	3
	9	AAM Part Number Read	S118963	VBF_SWDL ProtocolAccess-Transport DOIP_UNKNOWN_Target_ADDR	3
	10	TCU Part Number Read	S00031	Test Not Executed	2

Table 2 | Extraction of the history of faults in the period for Brake Fill.

Process	Index	Test Fix	DTC	DTC Description	Total cases
Brake fill	1	BCM Horn test	S00024	System abort (user)	28
	2	BCM Horn test	S10005	Operator Request aborted	27
	3	Online fill Combined	S58195	GGDS ProtocolAccess - Transport error-Connection failed	13
	4	Online fill Combined	BFF000	Rig Error	6
	5	Online fill Combined	S00024	System abort (user)	6
	6	BCM Horn test	V3507	Horn operation	6
	7	Online fill Combined	S120004	RR Communication Failure	5
	8	BCM Horn test	S50007	GGDS Protocol Disconnect Failure	4
	9	BCM Horn test	S50506	GGDS Protocol DoIP comms lost after retry	4
	10	Online fill Combined	S00007	Abort Timeout	3

Table 3 | Extraction of fault history for the period for EOL.

Process	Index	Test Fix	DTC	DTC Description	Total cases
EOL	1	RGTM Part number read All	S110013	VBF_SWDL Failed with no response / negative response	17
	2	DRDM Window test	V002	Routine Not OK	17
	3	PIVI Learn Config	S58963	GGDS ProtocolAccess- Transport DOIP _ UNKNOWN _TARGET_ADDR	11
	4	ICCM ODST	S58963	GGDS ProtocolAccess- Transport DOIP _ UNKNOWN _TARGET_ADDR	11
	5	ICCM DTC Read	S58963	GGDS ProtocolAccess- Transport DOIP _ UNKNOWN _TARGET_ADDR	11
	6	ICCM DTC Clear	S58963	GGDS ProtocolAccess- Transport DOIP _ UNKNOWN _TARGET_ADDR	11
	7	ICCMData Recording	S58963	GGDS ProtocolAccess- Transport DOIP _ UNKNOWN _TARGET_ADDR	11
	8	DADC ODST	E01A56	Control module main calibration data invalid / incompatible configuration	9
	9	RCM Field Mode DTC Clear	S00031	Test Not Executed	8
	10	RCM Part Number Read All	S110012	VBF_SWDL - Can't match the assembly	7

Table 4 | Extraction of the history of faults over the period for Fuel Pump Enable.

Process	Index	Test Fix	DTC	DTC Description	Total cases
Fuel Pump Enable	1	PCMB Aj200 Log Urea level	V4128	Outside specified limits	8
	2	Force ignition BCM1	S00023	System abort (software)	8
	3	Force ignition BCM1	S50018	GGDS module return code 0x12- Subfunction not supported	7
	4	BCM Normal mode	S50018	GGDS module return code 0x12- Subfunction not supported	7
	5	BCM Ignition check1	S00023	System abort (software)	7
	6	BCM Ignition check1	S20002	Delay operation aborted	7
	7	PRDM Window test	S00031	Test not executed	3
	8	DRDM Window test	V002	Routine Not OK	3
	9	PRDM Window calibration	S58199	GGDS ProtocolAccess - transport error - No responde	2
	10	PDM Window test	S00031	Test not executed	2

Table 5 | Extraction of the history of faults over the period for WAHA.

Process	Index	Test Fix	DTC	DTC Description	Total cases
WAHA	1	TCU GSM Communication	V2904	Response timeout	34
	2	Awaiting Vehicle centralising BR	S36016	MODBUSCOMMS abort signalled	15
	3	Wait Comms Check	S20002	Delay operation aborted	11
	4	Wait Comms Check	S00023	System abort (software)	9
	5	EOL process check	V3733	VCATS line process fail	6
	6	Wheel balancer angle check	V3926	Steering angle out of tolerance	5
	7	Wait WAHA process complete	S20002	Delay operation aborted	5
	8	PCM coolant pump test completed	V002	Routine Not OK	5
	9	HVAC run in test completed	V3958	HVAC run in test not completed	5
	10	Headlamp results	GEO020	Right headlamp fail	5

Table 6 | Extraction of the history of faults over the period for Rolling Road.

Process	Index	Test Fix	DTC	DTC Description	Total cases
Rolling Road	1	IPMA Reset	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	21
	2	IPMA DTC Read	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	21
	3	DADC Enable Rolling Road Mode	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	20
	4	TCU DTC Read	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	16
	5	ICCM Initialised check	V4166	Not Initalised	16
	6	ICCM Initialised check	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	16
	7	ICCM DTC Check	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	16
	8	ICCM AMFM Signal Strenght	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	16
	9	NFSM DTC Read	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	15
	10	AAM External Sounder Status Check	S58963	GGDS ProtocolAccess- Transport DOIP – UNKNOWN _TARGET_ADDR	13

Table 7 | Extraction of the history of faults in the period for Health Check.

Process	Index	Test Fix	DTC	DTC Description	Total cases
Health Check	1	RGTM Part number read All	S110013	VBF_SWDL - Failed with no response / negative response	23
	2	IPCB VIN write	S58963	GGDS ProtocolAccess- Transport DOIP _UNKNOWN _TARGET_ADDR	12
	3	IPCB Plant Mileage check	S58963	GGDS ProtocolAccess- Transport DOIP _UNKNOWN _TARGET_ADDR	12
	4	IPCB Part Number read All	S118963	VBF_SWDL ProtocolAccess-Transport DOIP_UN-KNOWN_Target_ADDR	12
	5	IPCB HW Check	S58963	GGDS ProtocolAccess- Transport DOIP _UNKNOWN _TARGET_ADDR	12
	6	IPCB DTC Read	S58963	GGDS ProtocolAccess- Transport DOIP _UNKNOWN _TARGET_ADDR	12
	7	IPCB Data Recording	S58963	GGDS ProtocolAccess- Transport DOIP _UNKNOWN _TARGET_ADDR	8
	8	PCM Fuel level Check	V3764	Fuel level low	6
	9	RGTM Part number read All	S118199	VBF_SWDL ProtocolAccess-Transport error no response	6
	10	AAM VIN write	S58963	GGDS ProtocolAccess- Transport DOIP _UNKNOWN _TARGET_ADDR	6

Table 8 | Extraction of the history of faults in the period for the Battery Health Check.

Process	Index	Test Fix	DTC	DTC Description	Total cases
Battery Health Check	1	Battery Voltage Check 1	V2905	Battery Voltage out of range	6
	2	Battery Voltage Check 1	S00031	Test not executed	3
	3	GNA Battery Bootup Box 1	S10005	Operator Request aborted	2
	4	GNA Battery Bootup Box 1	S00014	System Time out (test time)	2
	5	GNA Battery Bootup Box 1	S00031	Test not executed	1
	6	Connect battery box 1	S40101	I-probe not connected	1
	7	Check VIN protect lable	S10005	Operator Request aborted	1
	8	Check VIN protect lable	S00013	System time out (phase)	1
	9	Battery Voltage Check 1	S40101	I-probe not connected	1
	10	Connect battery box 1	S40101	I-probe not connected	1

From the identified failures, four were selected based on their significant impact on daily performance indicators. This selection was made with consideration for their impact on analysis time and the financial implications they entail for the company. Despite the heterogeneity of the failure modes, the modes targeted in this study would also yield substantial benefits for the process. The faults that were the focus of this research are enumerated in Table 9.

Table 9 | Failure modes defined for the research study.

Work Station	Fail Description	Effect
EOL	DRDM Windows test	Routine NOK
Health Check	RGTM part number read all	VBF_SWDL- Failed with no response / negative response
WAHA	TCU GSM communication	Response timeout
Brake Fill	BCM Horn test	System abort (user)

3.3 An analysis of the failure modes and their effects

Following the definition of the failure modes to be analysed, a survey of their effects was conducted in order to assist in the development of the research algorithm. The development of this algorithm entailed a comprehensive consideration of all potential effects associated with each DTC (Diagnostic Trouble Code). The algorithms employed for resolving these faults were meticulously constructed, as illustrated in Table 10.

Table 10 | Faults defined for analysis and their effects

Fault description				
	DRDM Windows test	**RGTM part number read all**	**TCU GSM communication**	**BCM Horn test**
Cause 1	Lack of supply voltage to the module	Operator did not follow Iview procedure	No power supply to the module	Breakdown of communication with the PLC
Cause 2	Module connector de-clipped	Trunk lid adjustment being carried out while the module is making the open and close adjustment	SW was not installed / wrong part number	Iview SW crashed while carrying out activity
Cause 3	Software installed on module was out of date	Software installed on module was out of date	Lack of GSM chip in module	Connector going to PCM module disconnected to PCM module disconnected
Cause 4	Internal module hardware fault	Internal module hardware fault	Disconnection of module antenna	Power failure
Cause 5	Broken window lifter	Trunk lid with geometry problem	Lack of external 4G signal for activation	Lost OBD connection cable
Cause 6	Build code mounted incorrectly			Operator didn't press the horn at the end of the process
Cause 7				Problem with I-View SW

3.4 Development of the algorithm for the automation of analyses

Subsequent to the identification of the causes for the defined faults, the algorithms began to be constructed on the basis of the matrix of faults and causes (Peeters, Basten and Tinga, 2018) shown in Table 10. For each fault, an algorithm was developed to automate the analysis process.

Each of the algorithms was applied to analyse their respective faults during a specific period, approximately three months, where the processes proposed by each diagram could be validated. The algorithms are shown in Figures 3 to 6.

Figure 3 | Algorithm for solving the DRDM module problem

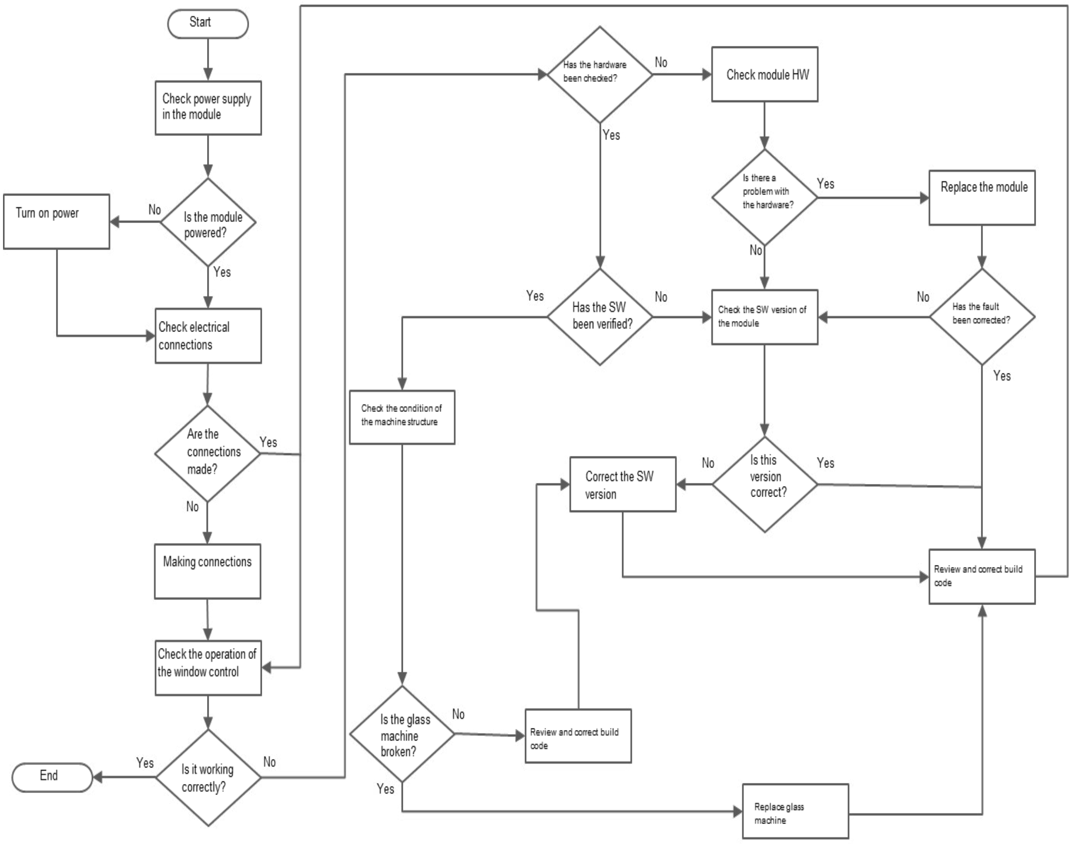


Figure 4 | Algorithm for solving the RTGM module problem

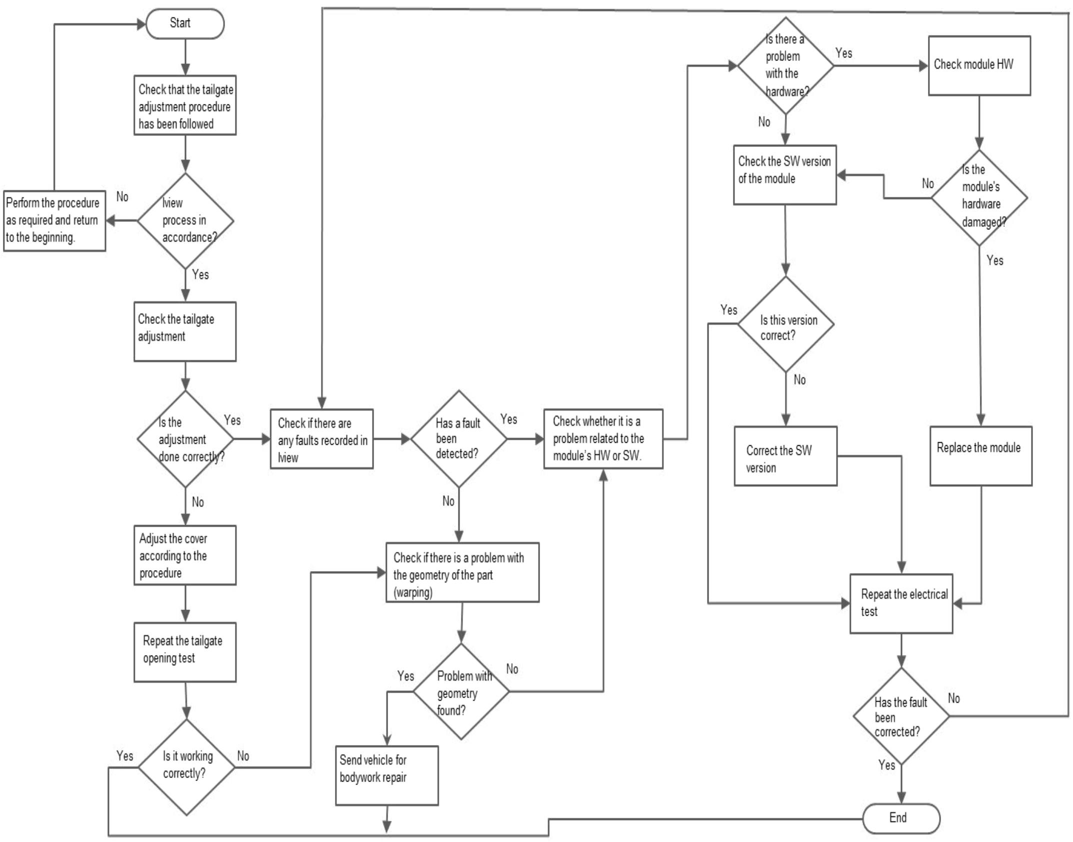


Figure 5 | Algorithm for solving the BCM Horn module problem

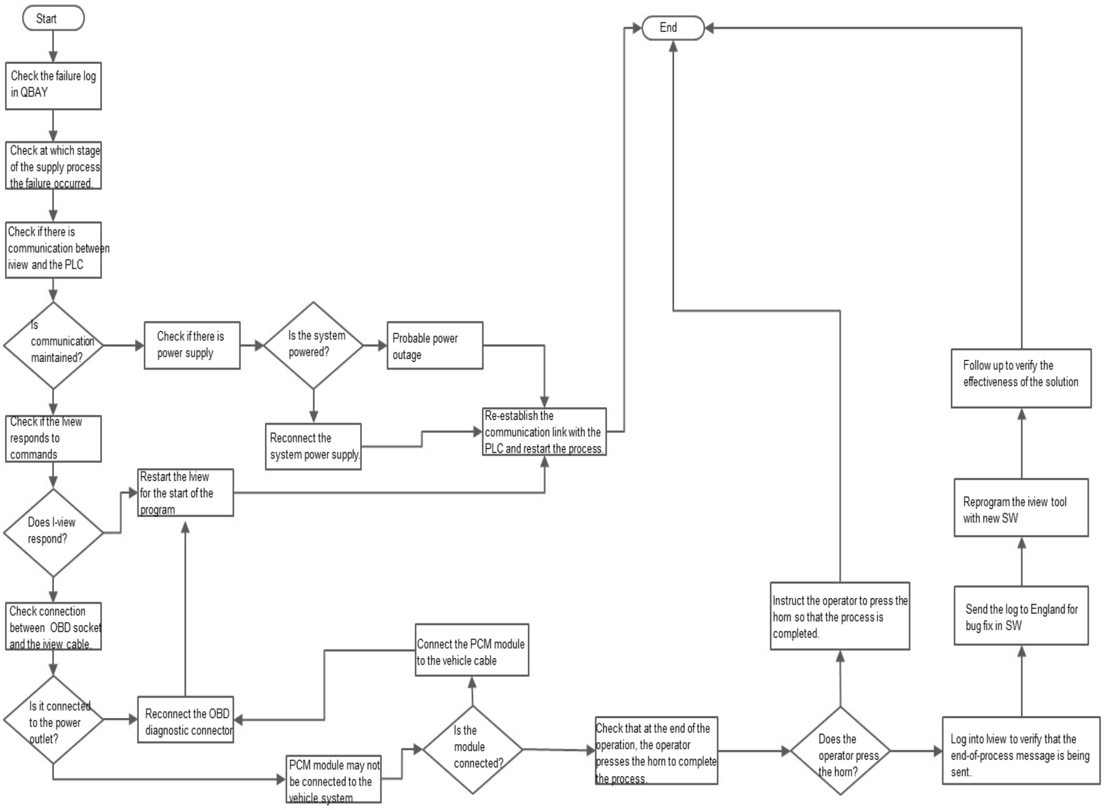
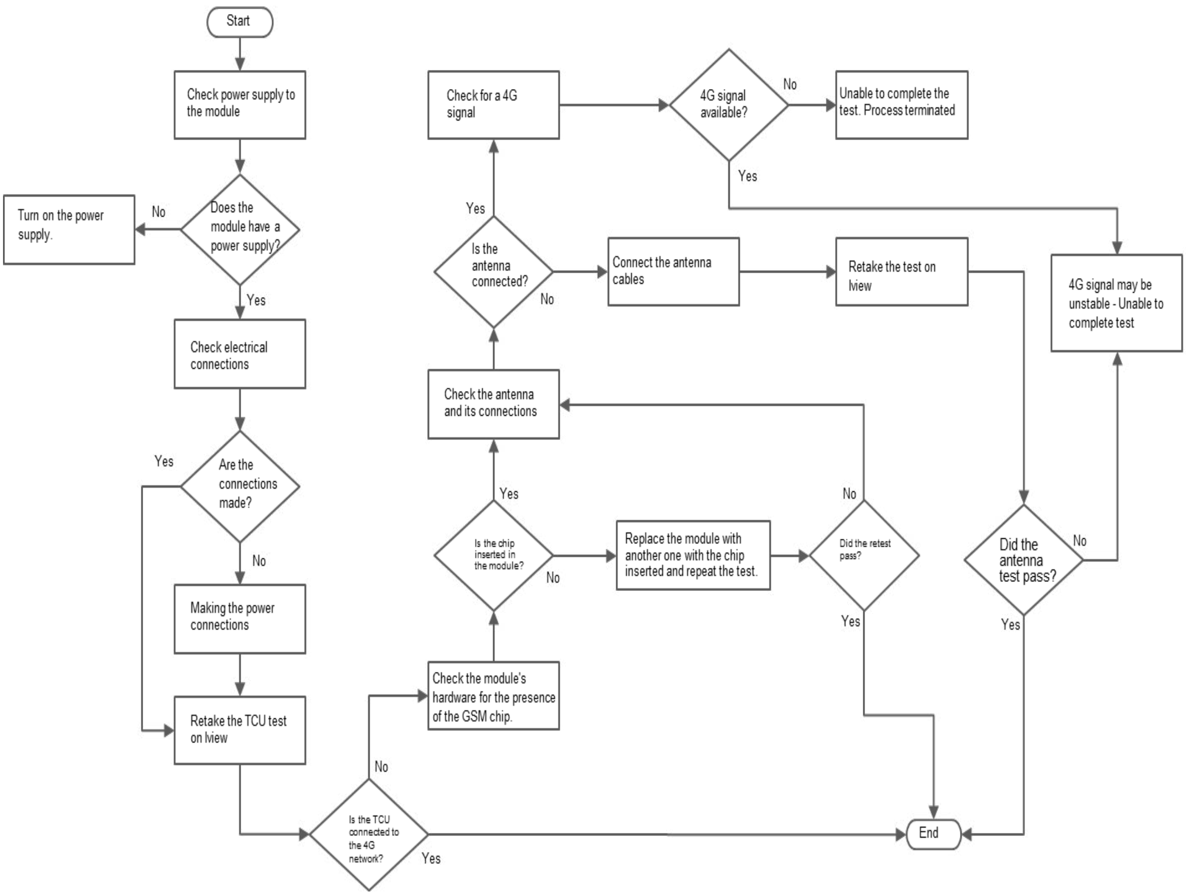


Figure 6 | Algorithm for solving the TCU module problem



4. TESTS AND RESULTS

As the algorithms were developed and completed, the flowcharts were applied to the analysis of the faults considered in this research. This analysis was used to measure the effectiveness of the algorithms for each incidence of problems on the production line within a predetermined period of three months.

In instances where a particular fault was identified during the research process, the algorithm was employed as a remedial measure. It is noteworthy that certain etiologies were identified as isolated occurrences, while others were observed to manifest with greater frequency. Consequently, in certain instances, the issues were resolved almost instantaneously.

However, the research identified a problem that necessitated a solution through an infrastructure project. The failure under consideration is that of the TCU, a communication module with the 4G network. This failure had a significant impact on the company's performance indicators and production, as the vehicle could not be removed from the production line with the support of pallet trucks due to its inability to start.

A multitude of analyses indicated an issue of instability in the 4G network. Consequently, the ultimate resolution entailed the implementation of amplifiers within the facility to augment the external signal, which experienced a significant diminution of power due to the considerable distance between the manufacturing plant and the operator's towers. The resolution of this issue was definitive within the period in which the research was conducted.

The subsequent figures illustrate the plant indicators by electrical parameterization stations subsequent to the implementation of the algorithms. It is imperative to acknowledge that the company utilizes two indicators to assess the enhancement in defect resolution on the production line. The initial indicator is RFT (Right First Time), which quantifies the number of "good firsts," defined as vehicles with zero defects during assembly. The secondary indicator is FTT (First Time Through), which assesses the efficacy of defects resolved on the line, i.e., faults repaired at the station without propagation. The implementation of these algorithms aimed to achieve this objective. As illustrated in Figure 7, the RFT indicator is a crucial element in this analysis.

Figure 7 | RFT indicator by electrical parameterization station after applying the algorithms.

Figures 8 to 15 show the extraction of the FTT according to the evaluation period with the resolution gains of the faults still on the line. It is important to note that these figures were taken from the QBAY electrical fault supervision system, which receives information from the process in real time.

The green bar is the correct result obtained the first time, the yellow bar is the amount of rework done on that line, and the red bar, in turn, is the faults that could not be repaired on the line. The FTT graph clearly illustrates the gains obtained by applying the algorithms.

Figure 8 | IPT FTT indicator.

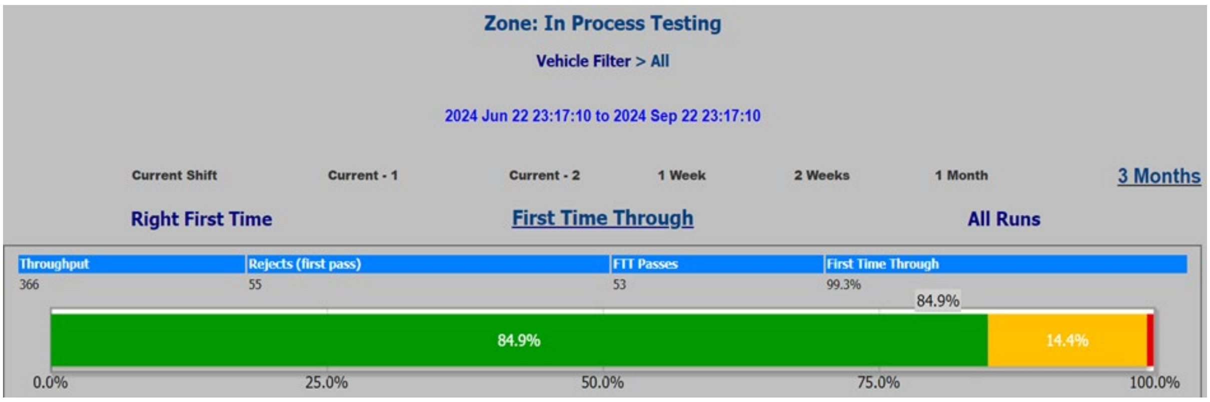


Figure 9 | Brake Fill FTT indicator.

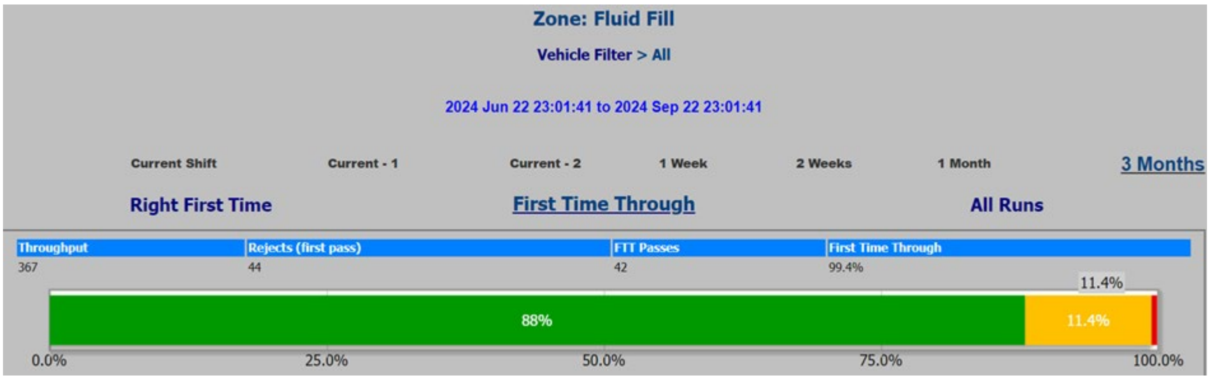


Figure 10 | FTT indicator of the EOL

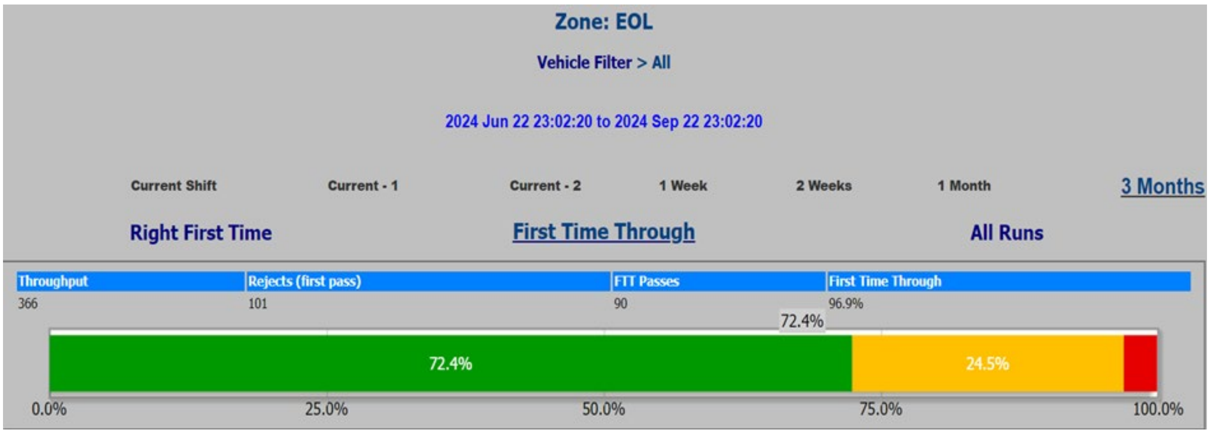


Figure 11 | Fuel Pump Enable FTT indicator

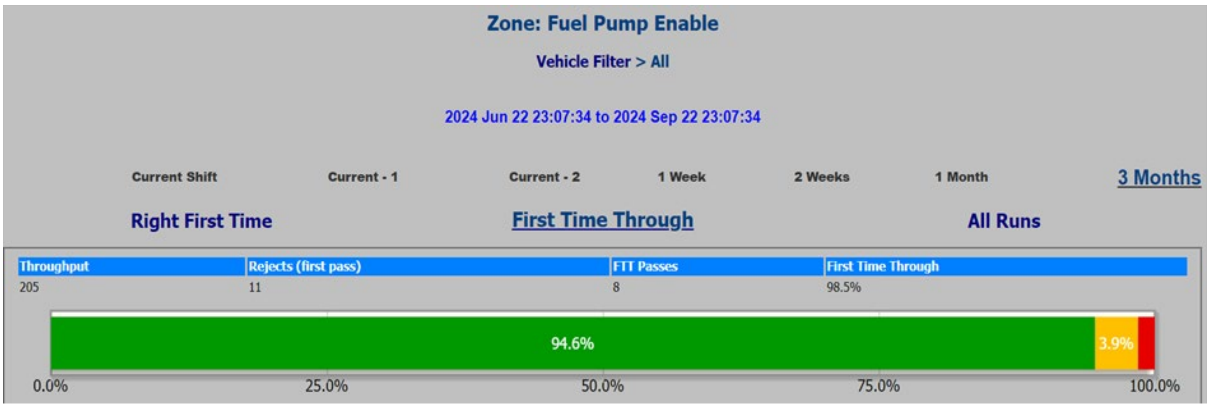


Figure 12 | WAHA FTT indicator

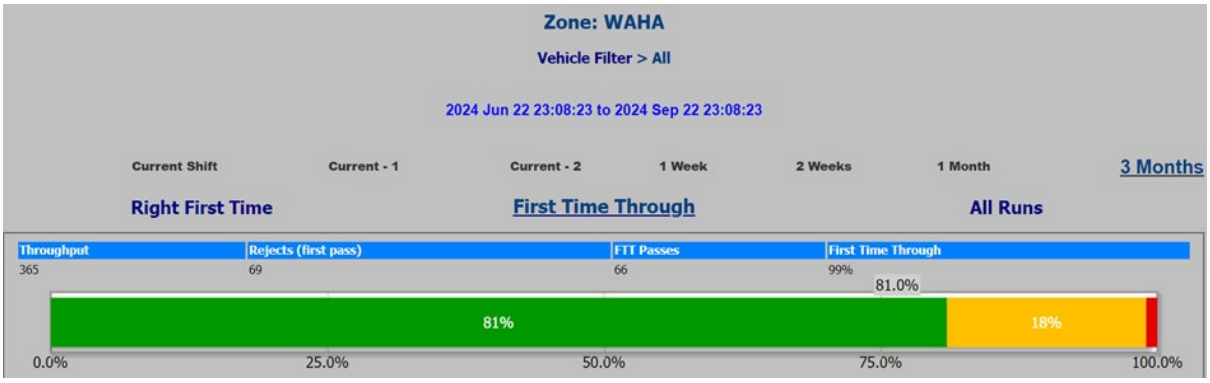


Figure 13 | FTT indicator of the Rolling Road test

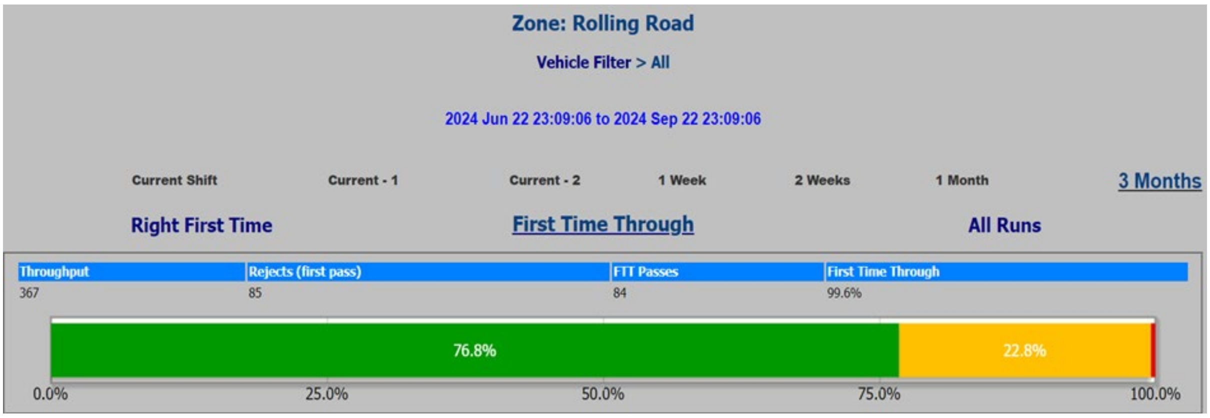


Figure 14 | Health Check FTT indicator

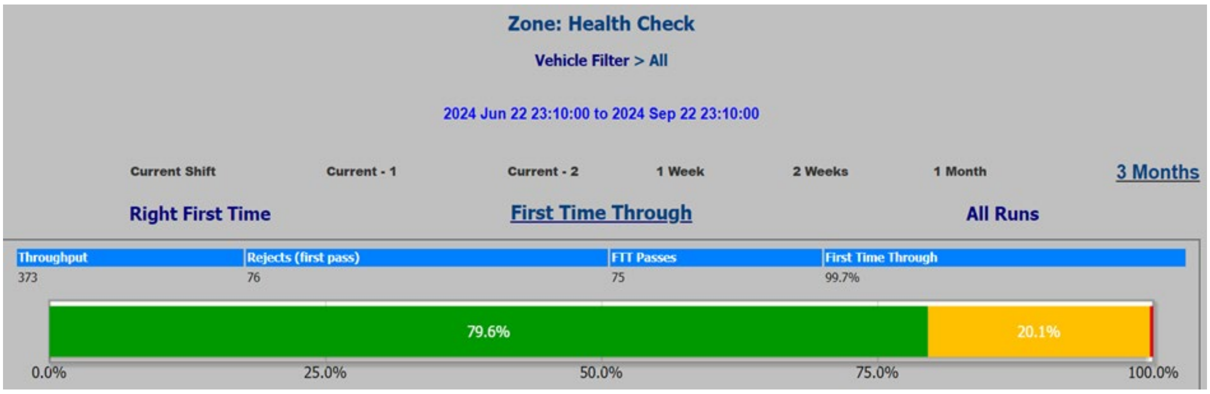
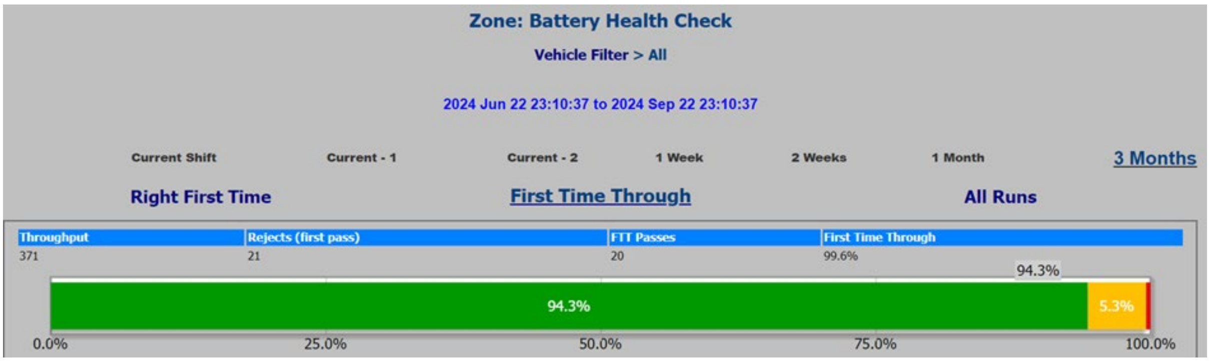


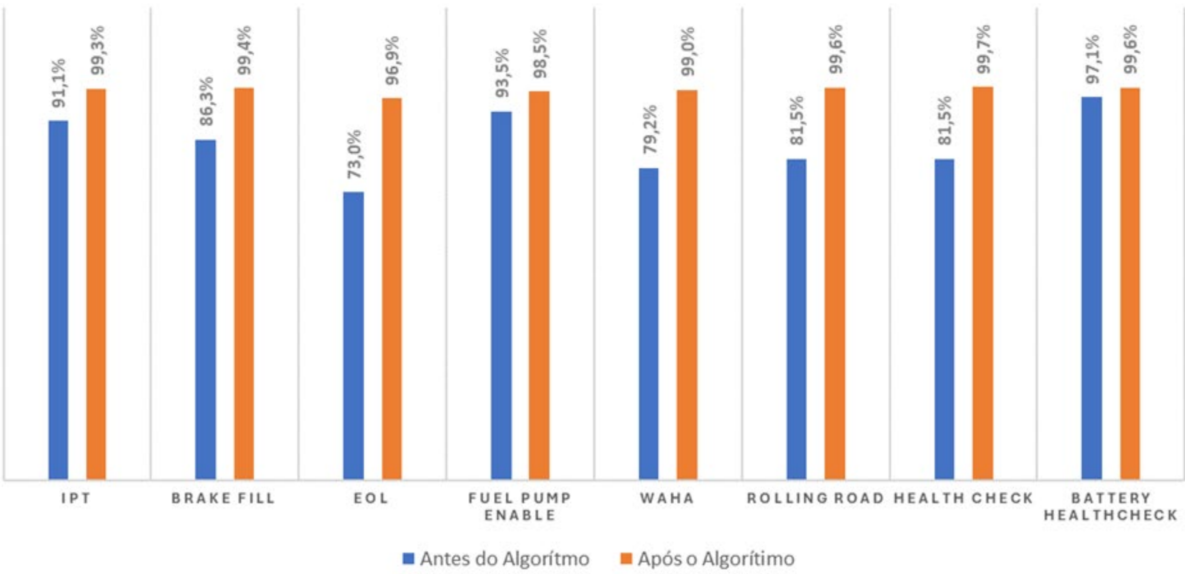
Figure 15 | Battery Health Check FTT indicator



To confirm the effectiveness of applying algorithms in resolving faults, Figure 16 shows a comparison between the results before and after applying the algorithms, confirming the improvement in the production process.

Significant gains can be seen in some positions in the graph, such as in EOL, where a gain of approximately 24% was achieved, demonstrating the effectiveness of applying algorithms in the process.

Figure 16 | Comparison between the results obtained before and after applying the algorithms



5. CONCLUSION

The application of algorithms in automation tasks is now standard practice, yielding positive outcomes for industry in terms of cost reduction and risk mitigation in the process, as well as ensuring operational stability. A superior algorithm is one that solves the task with minimal intervention during execution.

The automation of analysis tasks can also be advantageous to the industry, since analysis tasks with possible known causes within a controlled production line environment (dos Reis et al., 2019), and without much external interference, can be automated in order to reduce troubleshooting time within the process. This automation has been shown to reduce execution time in the operation, which is of particular importance in the context of automotive manufacturing.

The algorithms proposed in this research demonstrated efficacy in their application, generating a gain of up to 28.2% in repairs within the production line, reducing the time previously spent on fault searches, and in some particular situations, due to the repeatability of a certain fault mode, leading to a definitive solution in the pilot plant used for testing the proposal. It is acknowledged that improvements can be made and other algorithms can be developed to automate the search for other faults (Shi et al., 2023), and the proposal presented in this article demonstrates this.

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