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Simulation Based Analysis of the Hierarchical Timed Coloured Petri Net Model for Automobile Maintenance Service Centre

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Abstract **Original Research Article**

Automobile maintenance service centres operate as complex discrete-event systems in which multiple maintenance activities are executed concurrently while competing for limited service resources. Inefficient scheduling, prolonged vehicle waiting time, queue congestion, and poor resource utilization continue to reduce service efficiency and customer satisfaction. Although Hierarchical Timed Coloured Petri Nets (HTCPNs) have demonstrated considerable capability for modelling concurrent systems, limited studies have investigated their application to the simulation and performance evaluation of automobile maintenance service centres involving both engine servicing and running repairs. This study presents the simulation of an HTCPN model developed for an automobile maintenance service centre using DDD Motors Service Centre as a case study. Operational data comprising vehicle arrivals, service commencement times, service completion times, and maintenance categories were collected over one month and analysed using the ARENA Input Analyzer to determine stochastic input distributions. The HTCPN model was implemented in CPN Tools and simulated under five operational scenarios representing different resource allocation policies. System performance was evaluated using six performance indicators: Vehicle Average Waiting Time (VAWT), Vehicle Average Service Time (VAST), Vehicle Average Time of Stay (VAST/TOS), Vehicle Average Queue Number (VAQN), Average Serviced Vehicles (ASV), and Average Leftover Vehicles (ALOV). The simulation results indicate progressive improvement in operational performance across the scenarios. Scenario 5 produced the lowest VAWT (4.02 min), VAST (122.17 min), VAST/TOS (126.19 min), VAQN (10.22), and ALOV (1), while increasing ASV to 41 vehicles. Statistical validation using an independent-samples *t*-test revealed no significant difference between simulated and observed serviced vehicles ($p = 0.618$), confirming the validity of the simulation model. The study demonstrates that HTCPN simulation provides an effective decision-support framework for evaluating alternative operational policies and improving service efficiency in automobile maintenance service centres.

Keywords: Automobile maintenance, Hierarchical Timed Coloured Petri Nets, Simulation, CPN Tools, Service operations, Discrete-event systems. Scenario Analysis.

INTRODUCTION

The automotive industry has undergone significant technological transformation over the past decade owing to advances in vehicle electrification, embedded control systems, onboard diagnostics, intelligent transportation systems, and digital connectivity (Sharma *et al.*, 2023; Wang *et al.*, 2023). Modern automobiles integrate sophisticated mechanical, electronic, and software components that require specialized maintenance procedures, advanced diagnostic equipment, and highly skilled technicians to ensure safe and reliable operation throughout their service life (Wang *et al.*, 2023). Consequently, automobile maintenance service centres (AMSCs) have evolved from conventional repair workshops into complex service organizations that combine technical maintenance activities with information management, customer service, spare-parts logistics, and operational planning (Sharma *et al.*, 2023).

The increasing technological sophistication of automobiles has substantially changed maintenance practices and service delivery. Contemporary vehicles incorporate electronic control units (ECUs), advanced driver assistance systems (ADAS), onboard diagnostic (OBD) systems, sensors, and communication networks that require systematic diagnostic procedures before maintenance interventions can be performed (Wang *et al.*, 2023). This evolution has increased the complexity of maintenance operations by requiring effective coordination among technicians, diagnostic equipment, service bays, maintenance schedules, and spare-parts inventories (Yadav *et al.*, 2023). Consequently, automobile maintenance service centres are increasingly recognized as complex discrete-event service systems in which multiple maintenance activities are executed concurrently while competing for limited operational resources (Nwogu *et al.*, 2023).

Efficient maintenance operations play a critical role in improving vehicle reliability, operational safety, customer satisfaction, and organizational productivity. Well-managed maintenance services reduce vehicle downtime, improve workshop throughput, and enhance the utilization of maintenance resources, thereby contributing to the sustainability and competitiveness of automobile service organizations (Yadav *et al.*, 2023). Conversely, inefficient maintenance operations often result in prolonged vehicle waiting times, service delays, workshop congestion, excessive queues, increased operating costs, and reduced customer confidence (Nwogu *et al.*, 2023). These operational challenges are particularly evident in high-demand maintenance centres where customer arrivals, service requests, technician availability, and repair durations vary continuously throughout the working day.

Automobile maintenance service centres typically consist of several interrelated processes, including customer reception, vehicle inspection, fault diagnosis, engine servicing, running repairs, quality assurance, vehicle washing, billing, and final vehicle delivery (Sharma *et al.*, 2023). These activities are highly interdependent because delays occurring in one process frequently propagate throughout the entire maintenance workflow. For example, shortages of technicians, unavailability of spare parts, prolonged diagnostic activities, or limited service-bay capacity may significantly increase customer waiting time and reduce overall system performance (Nwogu *et al.*, 2023). Such operational characteristics indicate that automobile maintenance service centres exhibit the fundamental properties of discrete-event systems, including concurrency, synchronization, resource sharing, queue formation, and stochastic event occurrence.

The growing demand for improved maintenance efficiency has encouraged the adoption of digital technologies and intelligent maintenance management systems. Recent developments in predictive maintenance, artificial intelligence, cloud computing, Internet of Things (IoT), digital twins, and data-driven analytics have transformed maintenance management from reactive repair activities into proactive and predictive service operations (Hoffmann and Lasch, 2023; Sanchez-Londono *et al.*, 2023a). These technologies facilitate continuous monitoring of equipment condition, intelligent fault diagnosis, optimized maintenance scheduling, and data-driven decision-making, thereby improving maintenance effectiveness and reducing operational downtime (Hoffmann and Lasch, 2023). Nevertheless, the successful implementation of these technologies depends on accurate system models capable of representing maintenance workflows and evaluating alternative operational strategies before their implementation in real service environments (Sanchez-Londono *et al.*, 2023b).

Simulation has therefore become an indispensable technique for analysing and improving maintenance service systems. Unlike analytical approaches that often require restrictive assumptions, simulation can represent stochastic arrivals, variable service durations, resource constraints, queue dynamics, and concurrent maintenance activities within realistic operational environments (Liu *et al.*, 2025). Simulation models enable maintenance managers to evaluate different operational scenarios, analyse system behaviour, estimate resource requirements, identify bottlenecks, and optimize maintenance performance without disrupting actual workshop operations (Liu *et al.*, 2025). Consequently, simulation has become an important decision-support tool for maintenance planning, operational analysis, and service system optimization across numerous industrial sectors.

Among the various modelling techniques for discrete-event systems, Petri Nets have received considerable attention because of their rigorous mathematical foundation and their ability to model concurrency, synchronization, resource allocation, and event sequencing within complex systems. Advanced Petri Net formalisms, particularly Hierarchical Timed Coloured Petri Nets (HTCPNs), extend these capabilities by incorporating hierarchical decomposition, temporal information, and coloured tokens into a single modelling framework. These features enable HTCPNs to represent multiple interacting entities, resource constraints, and time-dependent operational activities while supporting formal verification and simulation-based performance evaluation (Jensen and Kristensen, 2009). Consequently, HTCPNs provide a suitable modelling framework for analysing the dynamic behaviour of automobile maintenance service centres and evaluating alternative operational policies before implementation.

The application of simulation-based HTCPN models is particularly important for automobile maintenance service centres operating in developing economies, where increasing vehicle ownership has intensified demand for maintenance services without corresponding improvements in workshop capacity and operational efficiency. Under such conditions, service centres frequently experience long queues, excessive vehicle waiting times, prolonged service durations, inefficient utilization of technicians and service bays, and delayed vehicle delivery (Nwogu *et al.*, 2023). These operational challenges highlight the need for robust simulation models capable of representing maintenance workflows, evaluating alternative resource allocation strategies, and supporting evidence-based decision-making for service process improvement.

Despite advances in automotive technologies, the operational performance of many automobile maintenance service centres remains unsatisfactory due to prolonged vehicle waiting times, inefficient queue management, extended service turnaround times, poor technician utilization, and delays in vehicle delivery. These challenges result from the concurrent execution of multiple maintenance activities, shared resource constraints, uncertain service durations, and ineffective scheduling of technicians, service bays, and equipment. As complex discrete-event systems characterized by concurrency, synchronization, timing constraints, and resource competition, automobile maintenance service centres require modelling and simulation techniques capable of accurately capturing their dynamic operational behaviour for effective performance evaluation and decision support.

Recent studies have demonstrated the growing application of Petri Nets and their extensions in modelling complex maintenance systems because of their ability to represent concurrency, synchronization, resource sharing, and dynamic system behaviour. Hierarchical, coloured, timed, and stochastic Petri Nets have been successfully applied in aircraft maintenance, mechatronic systems, and industrial maintenance to support reliability analysis, fault diagnosis, maintenance planning, and performance optimization (Abbes *et al.*, 2025; Mehdi *et al.*, 2024; Badmus *et al.*, 2025; Hristoski *et al.*, 2025; Benzoni *et al.*, 2025). More recently, hybrid Petri Net frameworks integrated with artificial intelligence and optimization techniques have enhanced maintenance decision-making by incorporating degradation prediction, uncertainty modelling, and resource optimization (Meghoe *et al.*, 2024).

Within automobile maintenance service centres, operational efficiency is strongly influenced by queue discipline, resource allocation, and service scheduling (Dehantoro *et al.*, 2016). Previous studies have identified major challenges facing service centres, including increasing vehicle complexity, technological advancements, skilled labour shortages, equipment requirements, and the growing demand for high-quality service (James *et al.*, 2020). Other researchers have proposed web-based management systems to improve administrative functions such as customer, inventory, and employee management (Vedant *et al.*, 2023). Although discrete-event simulation has been shown to effectively evaluate bottlenecks, service times, and resource utilization in vehicle maintenance operations (Silva *et al.*, 2025), such models generally lack the formal verification and structural representation provided by Hierarchical Timed Coloured Petri Nets. Consequently, there remains a need for validated HTCPN-based simulation models capable of representing integrated automobile maintenance processes and supporting comprehensive performance evaluation of service-oriented indicators such as waiting time, queue length, throughput, and resource utilization.

Although Petri Nets and their extensions have been widely applied to maintenance, manufacturing, transportation, and production systems, their application to integrated automobile maintenance service centres remains limited. Existing studies have largely employed conventional Petri Net models that inadequately represent heterogeneous maintenance activities, hierarchical process structures, timing behaviour, and resource interactions typical of modern workshops. Moreover, service-oriented performance measures such as vehicle waiting time, service time, queue length, throughput, and resource utilization have received relatively little attention, while rigorous validation using operational data from real service centres is scarce. These limitations highlight the need for a validated Hierarchical Timed Coloured Petri Net (HTCPN) simulation framework capable of modelling integrated automobile maintenance operations and supporting the evaluation of alternative operational scenarios for improved service performance.

The study by Salawu *et al.* (2026) represents a significant contribution to the application of Hierarchical Timed Coloured Petri Nets (HTCPNs) in automobile maintenance systems through the development of a comprehensive, modular, and hierarchical model that integrates the major operational processes of an automobile maintenance service centre, including arrival–reception, engine service, running repair, and quality assurance. Unlike many previous studies that focused on isolated maintenance activities or specific service units, the developed HTCPN model provides a robust formal representation of the complete maintenance workflow, incorporating concurrency, timing, resource allocation, coloured tokens, guard functions, and hierarchical decomposition. Consequently, the model provides a sound theoretical and structural foundation for modelling complex automobile maintenance operations and serves as an important reference framework for subsequent research.

Although the study established the logical correctness of the developed HTCPN model through structural verification and demonstrated its capability to represent the operational behaviour of an automobile maintenance service centre, the model was not subjected to comprehensive simulation-based performance analysis and validation under alternative operational conditions. Specifically, the developed model was not used to evaluate the effects of different staffing configurations, service bay capacities, vehicle arrival patterns, service scheduling policies, or resource allocation strategies on the operational performance of the maintenance centre. As a result, the optimal operating conditions and performance limits of the developed model remain unexplored.

Recognizing this limitation, Salawu *et al.* (2026) recommended that future research should extend the developed HTCPN model through comprehensive simulation-based performance analysis using real operational data and multiple operational scenarios to evaluate key performance indicators such as vehicle waiting time, service time, queue length, throughput, and resource utilization. The authors further suggested that the model could subsequently be integrated with optimization techniques and intelligent decision-support approaches to enhance maintenance service delivery.

This recommendation provides the principal motivation for the present study. Rather than developing a new HTCPN model, this research adopts the validated HTCPN model developed by Salawu *et al.* (2026) as the baseline simulation model and subjects it to extensive simulation experiments under different operational scenarios. By systematically varying critical operational parameters, including staffing levels, service capacity, and resource allocation, the study seeks to evaluate the dynamic behaviour of the maintenance system and determine optimal operational configurations that minimize vehicle waiting time and queue length while maximizing throughput and resource utilization. The simulation-based analysis therefore bridges the gap between model development and operational optimization, transforming the previously developed HTCPN model into a practical decision-support tool for evidence-based management of automobile maintenance service centres.

Accordingly, this study extends the contribution of Salawu *et al.* (2026) by demonstrating the practical applicability of the developed HTCPN model through simulation, performance evaluation, scenario analysis, and operational optimization. The findings are expected to provide maintenance managers with quantitative evidence for selecting optimal resource configurations, improving service efficiency, reducing operational bottlenecks, and enhancing customer satisfaction, while also establishing a framework for future integration of HTCPN simulation models with optimization algorithms, artificial intelligence, and machine learning techniques for intelligent maintenance management.

DESCRIPTION OF THE CASE STUDY

The developed Hierarchical Timed Coloured Petri Net (HTCPN) model was developed using operational data obtained from an authorized automobile maintenance service centre. Data were collected over a one-month period during normal operating hours (Monday–Friday: 8:00 am–5:00 pm; Saturday: 10:00 am–3:00 pm). The service centre comprises four major operational units: vehicle reception and parking, information desk/reception, workshop operations, and quality control. Upon arrival, vehicles are registered, assigned service tags, and processed on a first-come-first-served basis before undergoing preliminary diagnosis to determine the required maintenance activities.

The workshop operation includes engine servicing, running repairs, body shop, and electrical services. This study focuses on engine servicing and running repair operations because they account for the majority of workshop activities and are the primary sources of queue congestion and service delays. Engine servicing involves routine maintenance operations, whereas running repairs include activities such as brake pad replacement, wheel alignment, and alternator replacement. The operational workflow and service-time data obtained from these processes were used to develop, parameterize, and validate the HTCPN simulation model for evaluating system performance and alternative operational scenarios.

SIMULATION METHODOLOGY

Data Collection and Analysis of Results for Model Development

Operational data used to develop, parameterize, and validate the Hierarchical Timed Coloured Petri Net (HTCPN) model were collected from an automobile maintenance service centre over a 30-day observation period. Data were obtained through a combination of service logbook review, direct observation of workshop operations, and structured interviews with workshop personnel. The collected data included daily vehicle arrivals, number of vehicles serviced, leftover vehicles, service times for engine servicing and running repair operations, effective working hours, vehicle allocation to service bays, distribution of maintenance requests (engine service only, engine service with brake pad replacement, wheel alignment, or alternator replacement), and average inter-service queue network times. These data provided the operational parameters required for modelling vehicle arrivals, service processes, resource utilization, and queue behaviour.

In addition, detailed processing times for individual maintenance activities were recorded to define the timed transitions of the HTCPN model. Engine service operations required between 120 and 180 minutes, while brake pad replacement required between 45 and 90 minutes. The collected operational data were subsequently analysed using descriptive statistics to estimate system input parameters and key performance indicators, including vehicle waiting time, service time, throughput, queue length, and resource utilization. These parameters were used to configure the simulation model in CPN Tools and to validate the simulation outputs against the observed performance of the maintenance service centre.

The operational data collected from the case study were analysed to estimate the input parameters for the Hierarchical Timed Coloured Petri Net (HTCPN) simulation model. Vehicle arrivals were observed to occur randomly throughout the workshop operating hours; therefore, the arrival process was represented using the average hourly arrival rate. During the 30-day study period, a total of 1,240 vehicles arrived at the service centre, of which 1,167 were serviced, leaving 74 unserved vehicles. The average daily arrival, service, and leftover vehicles were 41.33, 38.90, and 2.47, respectively, while the average vehicle arrival rate was estimated as 4.97 vehicles per hour based on 250 effective working hours.

Queue analysis showed that vehicles requiring both engine servicing and running repairs experienced additional waiting between service sections. The average inter-service queue network time across the observation period was 39.33 minutes, indicating the presence of operational delays caused by resource sharing and workflow dependencies. Analysis of service demand further revealed that engine servicing constituted the majority of maintenance requests, with comparatively fewer vehicles requiring brake pad replacement, wheel alignment, or alternator replacement in addition to engine service.

Service times for all maintenance activities were estimated from the observed minimum and maximum processing times. The mean processing time for each activity was calculated as the midpoint of the corresponding minimum and maximum values, resulting in triangular probability distributions (minimum–mean–maximum) for all timed transitions in the HTCPN model. These distributions were used to parameterize the execution times of engine servicing, brake pad replacement, alternator replacement, and wheel alignment operations within the simulation model, thereby enabling realistic representation of process variability during simulation experiments.

Development of the HTCPN Model

According to Salawu *et al.*, (2026), the Hierarchical Timed Coloured Petri Net (HTCPN) model was developed to represent the workflow of the automobile maintenance service centre. To manage system complexity, the model was organized hierarchically into a main page and four interconnected submodules: Arrival–Reception, Engine Service, Running Repair, and Quality Assurance–Car Wash. The main page provides an integrated view of the maintenance systemas shown in figure 1, while each submodule models a specific operational stage and their interactions through shared resources and timed transitions.

The Arrival–Reception module models vehicle arrival, registration, fault reporting, diagnosis, job order generation, and payment processing. The Engine Service module captures routine maintenance activities, including vehicle scanning, oil servicing, battery disconnection and reconnection, engine testing, and final inspection as depicted in figure 2. Figure 3 portrayed the Running Repair module which represents repair operations such as brake pad replacement, wheel alignment, and alternator replacement, whereas the Quality Assurance–Car

Wash module models vehicle cleaning, quality inspection, and release to customers. Timed transitions were parameterized using field data, while coloured tokens were used to distinguish vehicle categories and maintenance requirements.

The hierarchical structure enables modular representation of concurrent processes, resource sharing, and synchronization, thereby facilitating simulation, performance evaluation, and verification of the automobile maintenance service centre.

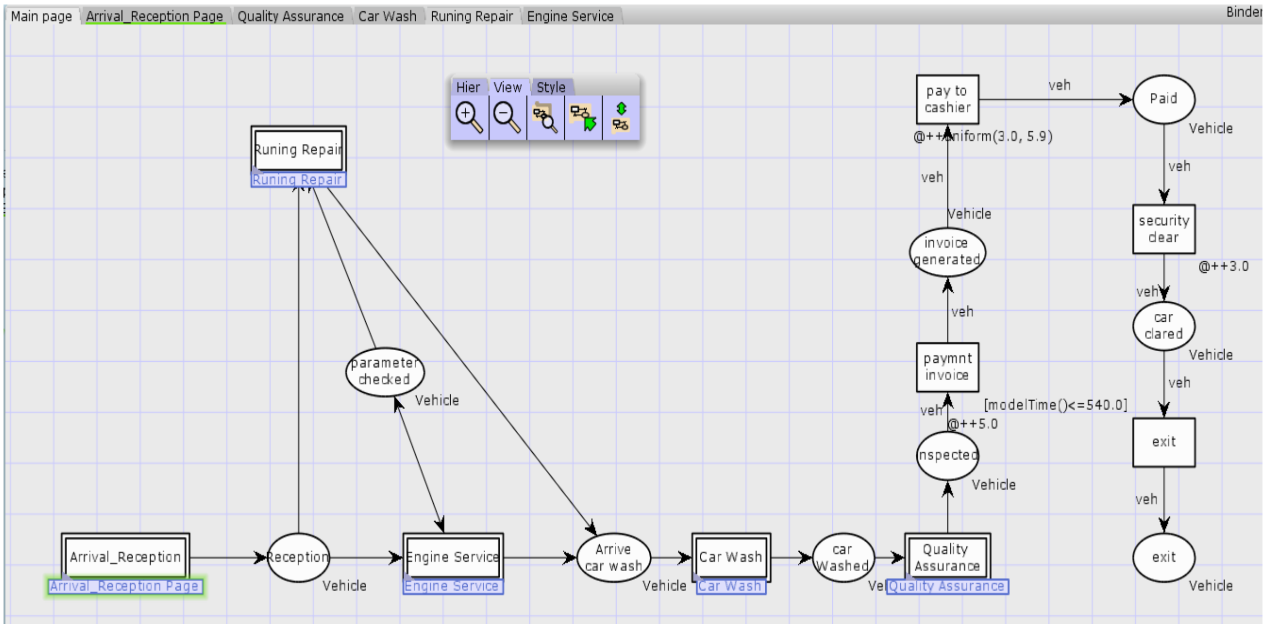

Figure 1: The Developed HTCPN model for Automobile Maintenance Service Centre flow processes (Source: Salawu *et al.* (2026))

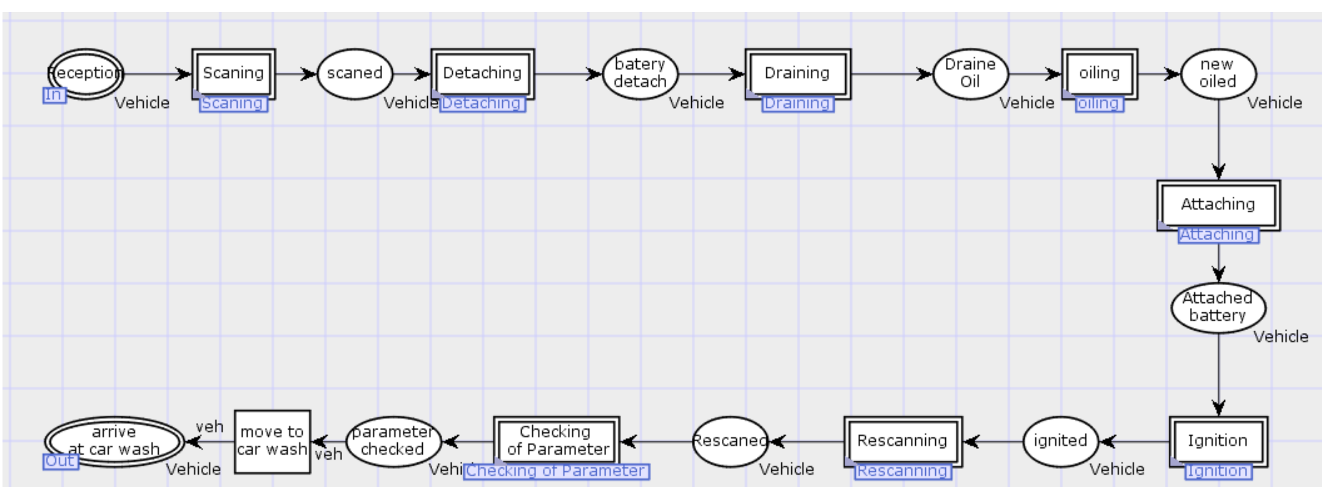

Figure 2: The Engine Service Module of the Developed HTCPN Model (Source: Salawu *et al.* (2026))

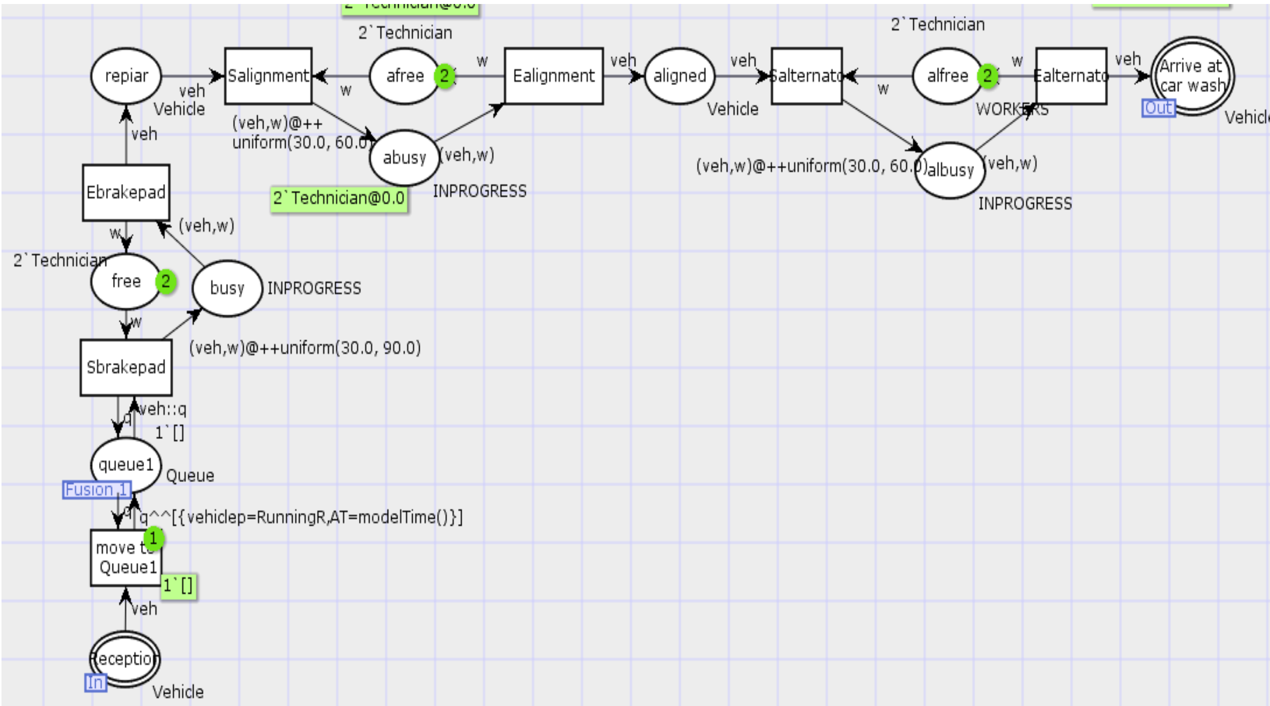

Figure 3: Running Repair Module of the Developed HTCPN Model (Source: Salawu *et al.* (2026))

Implementation and Simulation of the HTCPN Model

The developed Hierarchical Timed Coloured Petri Net (HTCPN) model for the automobile maintenance service centre was implemented and simulated using Coloured Petri Nets Tools (CPN Tools Version 4.0) on an Intel® Core™ i5 processor-based system. The simulation aimed to evaluate the operational performance of the maintenance service process using key performance indicators such as Vehicle Average Waiting Time (VAWT), Vehicle Average Service Time (VAST), Vehicle Average Queue Network (VAQN), Vehicle Average System Time (VAST/TOS), Average Serviced Vehicles (ASV), and Average Left Over Vehicles (ALOV).

A total of thirty simulation runs were conducted, with each run representing one operational day of the service centre. Five operational scenarios (as shown in Table 1) were analysed to examine the impact of resource allocation on system performance. Scenario 1 represented the existing operational condition of the service centre, while Scenarios 2 to 5 represented alternative operational configurations with increased personnel in selected service units

Specifically, Scenario 2 involved increasing the number of officers in the quality control section, Scenario 3 increased personnel in the scanning and car wash units, Scenario 4 increased the number of officers in the brake repair unit, while Scenario 5 increased the number of reception officers. The simulation results enabled comparative evaluation of the operational scenarios and provided insights into the effects of resource adjustments on waiting time reduction, service efficiency, queue minimization, and overall system performance within the automobile maintenance service centre.

Table 1: Matrix Representation of the Five (5) Experimented Scenarios

SN	Section/Unit	Experiment				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1	Reception	4	4	4	4	6
2	Scan	2	2	4	4	4
3	Detach Battery	2	2	2	2	2
4	Drain Oil	2	2	2	2	2
5	Put New Oil	2	2	2	2	2
6	Attach Battery	2	2	2	2	2
7	Run Ignition	2	2	2	2	2
8	Rescan	2	2	2	2	2
9	Parameter Check	2	2	2	2	2
10	Car Wash	2	2	4	4	4
11	Alignment	2	2	2	2	2
12	Alternator	2	2	2	2	2
13	Brake	2	2	2	4	4
14	Quality Control	2	4	4	4	4

Scenario 1 represents the current working conditions of case study
Scenarios 2,3,4 and 5 represent the probable future working conditions of the case study

RESULTS

Simulation Outcomes

Five scenarios were evaluated and the simulation results of the five (5) experimented scenarios based on the Performance metrics are as presented in Table **2**

Table 2: Simulation Results of the Five (5) Experimented Scenarios Based on the Performance Metrics

Matric	**Senario 1**	**Senario 2**	**Senario 3**	**Senario 4**	**Senario 5**
VAWT (min)	10	12.30	14.55	9.25	4.02
VAST (min)	152	143.30	136.70	129.58	122.17
TOS (min)	162	157	151.25	139.33	126.19
VAQN (min)	39.33	21.40	18.15	16.12	10.22
ASV	39	39	39	40	41
ALOV	3	3	3	2	1

MODEL VALIDATION

The developed Hierarchical Timed Coloured Petri Net (HTCPN) model was validated by comparing daily service counts from the simulation against actual data. Over a 30-day period (Table 3), the simulated number of serviced vehicles closely matched the real counts. For example, on Jan 4 both actual and simulated counts were 45 cars. Minor day-to-day differences (e.g. Jan 20: actual 22 vs simulated 24) were observed, but overall totals were nearly identical (30-day totals 1,167 vs 1,166).

The daily simulation closely tracked actual number of vehicles; most days differed by at most 1–2 vehicles.

Table 3: Daily Actual vs. Simulated Number of Serviced Vehicles.

SN	Day/ Date of Arrived	Actual (cars)	Simulated (cars)
1	Tuesday, January 2, 2024	39	40
2	Wednesday, January 3, 2024	42	41
3	Thursday, January 4, 2024	45	45
4	Friday, January 5, 2024	41	40
5	Saturday, January 6, 2024	25	26
6	Monday, January 8, 2024	39	38
7	Tuesday, January 9, 2024	44	43
8	Wednesday, January 10, 2024	45	45
9	Thursday, January 11, 2024	44	43
10	Friday, January 12, 2024	39	39
11	Saturday, January 13, 2024	26	25
12	Monday, January 15, 2024	43	43
13	Tuesday, January 16, 2024	43	42
14	Wednesday, January 17, 2024	42	43
15	Thursday, January 18, 2024	44	44
16	Friday, January 19, 2024	38	37
17	Saturday, January 20, 2024	22	24
18	Monday, January 22, 2024	44	44
19	Tuesday, January 23, 2024	43	42
20	Wednesday, January 24, 2024	42	43
21	Thursday, January 25, 2024	40	39
22	Friday, January 26, 2024	41	42
23	Saturday, January 27 2024	20	19
24	Monday, January 29, 2024	42	41
25	Tuesday, January 30, 2024	43	44
26	Wednesday, January 31, 2024	43	43
27	Thursday, February 1, 2024	39	40
28	Friday, February 2, 2024	40	40
29	Saturday, February 3, 2024	26	27
30	Monday, February 5, 2024	43	44

A paired t-test was performed on the 30 days of counts (simulation vs. real) using SPSS. The results of the validation test yielded $t=0.516$ and $p=0.0618$, which exceeds the 0.05 significance threshold as indicated on Table 4. By standard statistical practice, a p-value > 0.05 means the null hypothesis (that simulated and actual means are equal) is not rejected. In other words, there is no statistical evidence of a difference between the two data sets (actual and simulated). Thus at the 5% significance level, the simulation output does not differ significantly from the real data ($p = 0.618$). This lack of a significant difference confirms that the HTCPN model faithfully reproduces the system's performance.

Table 4: Summary of Statistical Analysis of the Validation Results of the Developed Model

Variable	t-value	p-value	Remark
Actual Number of service car – Simulated Number of service car	0.516	0.618	Since p-value is greater than 0.05, there is no significant difference between the real data and simulated data (Number of Serviced car) at 5% significant level

In summary, the validation results show excellent agreement between simulated and actual service vehicles. The non-significant t-test result ($p > 0.05$) indicates the model's outputs are statistically indistinguishable from the observed data. Therefore, we conclude that the developed HTCPN simulation is valid and accurately represents the automobile maintenance service center's operations at the 5% significance level.

CONCLUSION

The HTCPN simulation model of the automobile maintenance service centre captured the full maintenance workflow (engine service and running repairs, including alignment, alternator, and brakes) and successfully evaluated staffing scenarios. Scenario 1 (the current configuration) showed that customer waiting time was highest at reception. Sequentially adding staff (Scenarios 2, 3, 4 and 5) in quality control, scanning/car wash, brakes, and reception reduced queues and lead times, with Scenario 5 yielding the best performance (shortest waiting/service times and highest throughput). Notably, simply adding personnel to one area shifted bottlenecks to others unless resources were balanced. For example, augmenting reception and brake staff had the greatest system-wide impact. These findings illustrate the value of targeted staffing adjustments for flow efficiency in complex service centers.

This work, an extension of Salawu *et al*. (2026) differs from prior studies (e.g. Dehantoro *et al.* (2016)) by modeling multiple entry points and pre-service steps (scanning, car wash, and parameter checks) and allowing concurrent servicing activities. This more detailed framework better reflects real operations, where vehicles can queue for different services simultaneously. Because the maintenance process is inherently hierarchical and time-driven, a Hierarchical Timed Coloured Petri Net was well suited to model it. The model's validity was confirmed by statistical testing: the paired t-test showed $t = 0.516$, $p = 0.618$, so the simulated serviced vehicles did not differ significantly from real data at $\alpha=0.05$. This agreement indicates that the HTCPN model reliably reproduces the center's dynamics.

In conclusion, this study simulated a well-developed and robust HTCPN-based model that integrates all major service processes and identifies optimal staffing strategies for a vehicle maintenance center. The model reduces excessive queuing from multi-service demands and enables quantitative performance improvement (fewer vehicles carried over, shorter waits, higher throughput). Its statistical validation and transferable framework make it a practical decision-support tool for similar service facilities. Overall, the contributions lie in providing a generalizable modeling approach that enhances operational efficiency and customer satisfaction in automotive service systems.

RECOMMENDATION FOR FUTURE RESEARCH

The findings of this study demonstrate that simulation-based analysis of the developed Hierarchical Timed Coloured Petri Net (HTCPN) model provides valuable insights into the operational performance of automobile maintenance service centres and supports evidence-based decision-making for service improvement. Building on these contributions, future studies should validate the experimented operational scenarios using real-time data collected from multiple automobile maintenance service centres to enhance the generalizability of the results across different operational environments. Comparative investigations involving authorized dealerships, independent garages, and public maintenance workshops would further establish the robustness and adaptability of the HTCPN modelling approach.

Future research should also integrate the developed HTCPN model with optimization techniques, such as metaheuristic algorithms, mathematical programming, or simulation optimization, to automatically determine optimal staffing levels, service bay capacities, scheduling policies, and resource allocation strategies. In addition, the incorporation of artificial intelligence and machine learning techniques for demand forecasting, predictive maintenance, and dynamic resource scheduling would enable the development of intelligent decision-support systems capable of adapting to changing operational conditions in real time.

Furthermore, the modelling framework may be extended to include additional workshop sections, such as electrical and body-shop repair units and operational factors such as spare-parts inventory management, technician skill levels, equipment failures, customer appointment scheduling, and maintenance cost analysis to provide a more comprehensive evaluation of service centre performance. Finally, the applicability of the HTCPN simulation framework should be investigated in other discrete-event service systems, including healthcare facilities, manufacturing systems, logistics centres, and transportation maintenance operations, where complex workflows, shared resources, and stochastic processes similarly influence operational efficiency. Such extensions would broaden the applicability of the proposed approach and further establish HTCPN simulation as a robust decision-support tool for the design, evaluation, and optimization of complex service systems.

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