Global Academic and Scientific Journal of Multidisciplinary Studies (GASJMS)

Volume 4 | Issue 7, 2026 Homepage: https://gaspublishers.com/gasjms/ ISSN: 2583-8970

Development of a Hierarchical Timed Coloured Petri Net Model for Automobile Maintenance Service Centre

Omotayo Salawu[1], Azeez Oyelami Ganiyu[2], Kadijat Funke Olagbenro[3], Rafiu Adesina Ganiyu[4] and Elijah Olusayo Omidiora[5]

[1]Department of Computer Scsience, Kwara State College of Education Oro, Kwara State, Nigeria
[2,3,4,5]Department of Computer Engineering, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria

Received: *11.06.2026* | ***Accepted:*** *11.07.2026* | ***Published:*** *14.07.2026*

***Corresponding Author:** Salawu Omotayo

DOI: *10.5281/zenodo.21353697*

Abstract **Original Research Article**

The increasing complexity of modern automobiles, coupled with the growing demand for efficient maintenance services, has intensified the need for robust process modelling techniques capable of improving service delivery in automobile maintenance service centres. Many service centres continue to experience operational challenges such as prolonged vehicle waiting times, excessive queue lengths, delayed service completion, and low resource utilization, leading to reduced customer satisfaction. Existing modelling approaches have primarily focused on isolated maintenance activities, particularly engine servicing, and are inadequate for representing integrated maintenance systems involving both engine service and running repair operations. This study presents the development of a Hierarchical Timed Coloured Petri Net (HTCPN) model for automobile maintenance service centres that captures the concurrent, stochastic, and hierarchical characteristics of maintenance processes. Operational data were collected from DDD Motors Service Centre, including vehicle arrival times, service commencement and completion times, and routing information for engine service and running repair activities. The collected data were analysed using the ARENA Input Analyzer to determine the probability distributions used as model input parameters. The proposed HTCPN model was developed using a hierarchical structure comprising a top-level module representing the overall maintenance workflow and four interconnected sub-modules: Arrival–Reception, Engine Service, Running Repair, and Quality Assurance–Car Wash. The model incorporates timed transitions, coloured tokens, guard functions, and hierarchical substitution transitions to accurately represent service processes, resource allocation, and vehicle movement through the maintenance system. Structural verification confirmed that the model is logically consistent, modular, scalable, and capable of representing concurrent maintenance operations without deadlocks. The developed HTCPN model provides a comprehensive framework for modelling integrated automobile maintenance service processes and establishes a reliable foundation for subsequent simulation, performance evaluation, and operational optimization. The proposed modelling approach offers an effective decision-support tool for improving service efficiency, reducing operational bottlenecks, and enhancing maintenance service delivery in automobile service centres and similar discrete-event systems.

Keywords: Hierarchical Timed Coloured Petri Net, Automobile Maintenance Service Centre, Modelling, Discrete Event Systems, Service Operations.

Citation: Salawu, O., Ganiyu, A. O., Olagbenro, K. F., Ganiyu, R. A., & Omidiora, E. O. (2026). Development of a hierarchical timed coloured Petri net model for automobile maintenance service centre. *Global Academic and Scientific Journal of Multidisciplinary Studies (GASJMS)*, 4(7), 8-24.

INTRODUCTION

Advances in automotive technology have transformed modern vehicles into complex systems integrating mechanical, electrical, electronic, and software components. Consequently, automobile maintenance service centres (AMSCs) have evolved from conventional repair workshops into technologically intensive service systems requiring effective coordination of technicians, diagnostic equipment, spare parts, customers, and information systems. These centres provide preventive, corrective, predictive, and condition-based maintenance services that are essential for ensuring vehicle reliability, operational efficiency, and customer satisfaction (Sharma et al., 2023; James et al., 2023; Kwakye et al., 2024).

The operation of an AMSC comprises interconnected activities, including customer reception, vehicle inspection, fault diagnosis, repair, quality assurance, billing, and vehicle delivery. The interdependence among these activities, coupled with shared resources such as technicians, service bays, and spare parts, makes maintenance service centres complex discrete-event systems. Inefficiencies in any stage of the workflow may propagate throughout the system, resulting in longer vehicle turnaround times, poor resource utilization, increased operating costs, and reduced customer satisfaction (James et al., 2020). These challenges are particularly pronounced in developing countries, where inadequate infrastructure, limited diagnostic facilities, and shortages of skilled personnel further constrain maintenance operations (Nguyen et al., 2023; Li et al., 2024; Kaid et al., 2023).

Several modelling approaches have been applied to analyse maintenance operations, including queueing theory, optimization methods, and discrete-event simulation. While these techniques provide valuable insights into resource utilization and operational performance, they often rely on simplifying assumptions or lack the formal mathematical structure required for rigorous verification and scalable model development. Consequently, formal modelling techniques have gained increasing attention for representing complex maintenance systems involving concurrency, synchronization, and resource sharing.

Among these techniques, Petri Nets have become one of the most widely adopted formalisms for modelling discrete-event systems because they integrate graphical representation with mathematical rigor. Their capability to model concurrent activities, synchronization, conflicts, and resource allocation while supporting formal verification and performance analysis makes them particularly suitable for analysing complex maintenance service operations (Jensen and Kristensen, 2009; Gehlot, 2019). These characteristics provide a strong foundation for developing advanced Petri Net models capable of accurately representing the dynamic behaviour of automobile maintenance service centres.

Petri Nets (PNs) are well-established mathematical and graphical modelling formalisms for representing discrete-event systems characterized by concurrency, synchronization, resource sharing, and asynchronous event execution. A classical Petri Net comprises four fundamental elements: places, transitions, arcs, and tokens, which collectively describe system states, activities, and state changes. The firing mechanism enables the representation of concurrent processes and resource interactions, making Petri Nets particularly suitable for modelling dynamic systems (Jensen and Kristensen, 2009; Gehlot, 2019).

Although classical Petri Nets provide a rigorous framework for behavioural analysis, their application to large-scale systems is constrained by limited data representation and state-space explosion. To overcome these limitations, Coloured Petri Nets (CPNs) were introduced, allowing tokens to carry data values (colours) that distinguish different entity types within a single model. This extension significantly improves model compactness, scalability, and flexibility while preserving the analytical properties of classical Petri Nets (Jensen and Kristensen, 2009).

The incorporation of temporal information led to the development of Timed Coloured Petri Nets (TCPNs), in which timestamps are associated with coloured tokens to explicitly model processing times, waiting times, transportation delays, and service durations. Consequently, TCPNs support quantitative performance evaluation through discrete-event simulation, enabling the analysis of system throughput, resource utilization, queue lengths, response times, and bottleneck formation. These capabilities make TCPNs particularly suitable for service systems whose performance depends on both activity sequencing and execution time (Liu *et al*., 2018).

To improve the modelling of large and complex systems, Hierarchical Timed Coloured Petri Nets (HTCPNs) extend TCPNs by introducing hierarchical decomposition. This approach partitions a complex system into interconnected sub-models while preserving overall behavioural consistency, thereby improving readability, maintainability, scalability, and model reuse. HTCPNs combine colour, timing, hierarchy, and the formal Petri Net execution semantics to provide an integrated framework for modelling concurrent maintenance activities, resource allocation, synchronization, and workflow interactions (Orlov *et al*., 2021).

Compared with conventional modelling approaches such as queueing theory, flowcharts, Unified Modelling Language (UML), and conventional discrete-event simulation, HTCPNs offer several advantages. Queueing models often require restrictive assumptions regarding arrival and service processes, while flowcharts and UML primarily provide descriptive representations without formal behavioural verification. Similarly, many discrete-event simulation models lack mathematical semantics for structural analysis. HTCPNs overcome these limitations by integrating graphical modelling, formal verification, state-space analysis, and executable simulation within a unified framework (Jensen and Kristensen, 2009; Gehlot, 2019).

Recent studies demonstrate the growing application of coloured and hierarchical Petri Nets in maintenance engineering and Industry 4.0 environments. For example, Orlov *et al*. (2021) developed an HTCPN framework for maintenance planning in technological facilities, demonstrating improved resource allocation and maintenance scheduling. Likewise, Lu *et al*. (2019) applied stochastic coloured Petri Nets to maintainability evaluation by incorporating maintenance resources and logistics into a unified simulation model. Other studies have employed coloured Petri Nets for aircraft maintenance (Abbes *et al*., 2025), reliability assessment of mechatronic systems (Mehdi *et al*., 2024), fault diagnosis in intelligent manufacturing systems (Kaid *et al*., 2023), and dynamic system monitoring (Badmus *et al*., 2025). Collectively, these studies demonstrate the effectiveness of Petri Net-based models for analysing complex maintenance processes involving concurrency, uncertainty, and resource constraints.

Despite these advances, applications of HTCPNs to automobile maintenance service centres remain limited. Existing studies largely focus on industrial equipment, manufacturing systems, aircraft maintenance, or isolated automotive after-sales processes, with limited attention to integrated workshop operations. Moreover, few studies simultaneously represent customer reception, diagnosis, engine servicing, running repair, quality assurance, and vehicle delivery within a unified hierarchical framework based on empirical operational data. Consequently, there remains a need for formally verified, modular, and reusable HTCPN models capable of representing the complete operational workflow of automobile maintenance service centres while supporting subsequent simulation and performance evaluation.

Accordingly, this study develops a Hierarchical Timed Coloured Petri Net model for an automobile maintenance service centre using operational data collected from an authorized service facility. The developed model integrates hierarchical decomposition, coloured tokens, timed transitions, guard functions, and substitution transitions to provide a scalable and formally verified representation of maintenance operations that can support future simulation, performance analysis, and operational optimization.

METHODS

Formal Definition of Hierarchical Timed ColourePetri Net (HTCPN)

The proposed model is based on the formal definition of the Hierarchical Timed Coloured Petri Net (HTCPN) presented by Huang and Xu (2025). An HTCPN extends the classical Petri Net by integrating coloured tokens, timing mechanisms, and hierarchical decomposition to represent complex discrete-event systems with concurrency, synchronization, and resource sharing. Formally, an HTCPN is defined as:

HTCPN = (P, T, A, Σ, V, C, G, E, I, N, ML, Type)

where:

(P) and (T) denote the sets of places and transitions, (A) is the set of directed arcs, (\Sigma) represents colour sets (data types), (V) is the set of typed variables, (C) denote colour mapping, (G) is the Guard function, (E) represents the arc inscription function, (I) is the initial marking function, (N) denotes set of hierarchical modules (pages), (ML) is the set of module links (substitution transitions) and (Type) denote page type (prime or subpage)

Case Study Description and Operations

This study adopted DDD Motors Service Centre, an authorized, automobile maintenance centre, as the case study for developing the proposed Hierarchical Timed Coloured Petri Net (HTCPN) model. Operational data were collected over one month during working hours (Monday–Friday: 8:00 am – 5:00 pm and Saturday: 10:00 am – 3:00 pm). The operational structure of the service centre comprises four major sections: car park and security, information desk/reception, workshop operation, and quality control/assurance as shown in Figure 1. The car park and security section is responsible for vehicle admission, parking allocation, registration, and queue discipline based on the first-come-first-served policy. Vehicles are issued numbered tags upon arrival to maintain orderly service operations.

The information desk/reception unit serves as the complaint and assessment section where vehicle owners report faults and technicians conduct preliminary diagnosis. Based on the assessment, vehicles are assigned to the appropriate service units, namely engine service, running repair, body shop, or electrical unit. A job order specifying the required operations is then generated and attached to the vehicle. The workshop operation section constitutes the core service unit of the centre and consists of engine service, running repair, body shop, and electrical sections. The engine service unit handles routine maintenance activities such as engine oil replacement, brake oil servicing, power steering oil replacement, fuel system maintenance, and engine testing. Operations in this unit typically require between two and three hours.

The running repair unit addresses mechanical faults including suspension defects, brake pad replacement, clutch problems, wheel balancing and alignment, tyre servicing, alternator faults, and related maintenance activities. Service duration varies depending on the complexity of the identified fault and vehicle condition. general time schedule. Each of the operations has its minimum and maximum time schedule. The flowchart of the sequential operational processes and stages involved in running repair of the developed Automobile Maintenance Service model is shown in Figure 2 comprising both engine service and running repair processes Although the body shop and electrical units form part of the operational structure of the centre, this study focuses primarily on engine service and running repair operations because these units constitute the major sources of queue congestion and prolonged waiting time within the service system.

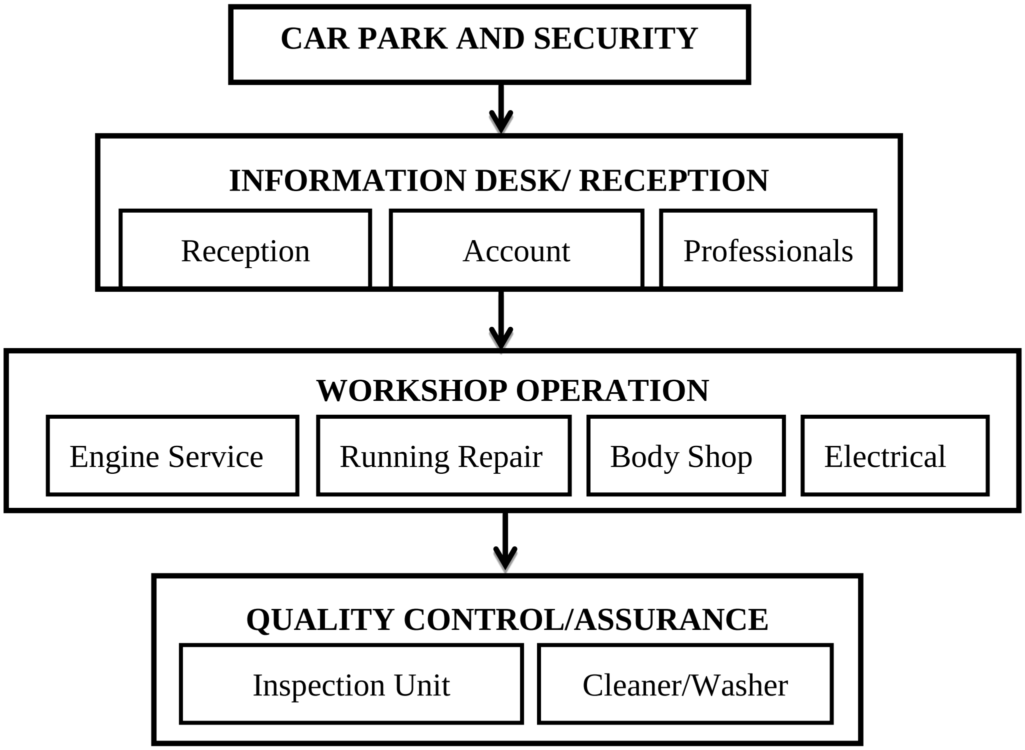

Figure 1: Hierarchical Operational Structure of Study System

Data Collection and Analysis

The methods used to collect data include a review of operational history (services log book), direct observation of the vehicles' arrival pattern, service time, and overall lead time and interview with staff at the workshop/ operation department of the centre. The following data were collected for analysis as depicted in table 1, Table 2, Table 3 and Table 4,: Table 5 depicts the **s**ummary of analysed input parameters used for the development of the Hierarchical Timed Coloured Petri Net (HTCPN) model for the automobile maintenance service centre.

i. Number of vehicle that arrived the centre daily
ii. Number of vehicle served daily
iii. Number of vehicle unattended (leftover) daily
iv. The service time at each stage of engine service and running repair operations
v. Effective working hour daily
vi. Average arrival per hour
vii. Daily allocation of vehicle to service bays
viii. Daily number of vehicles that either came for engine service only or engine service with any of the three running repair operations: Brake pad, alignment and alternator replacement
ix. Average Queue Network Time per day.

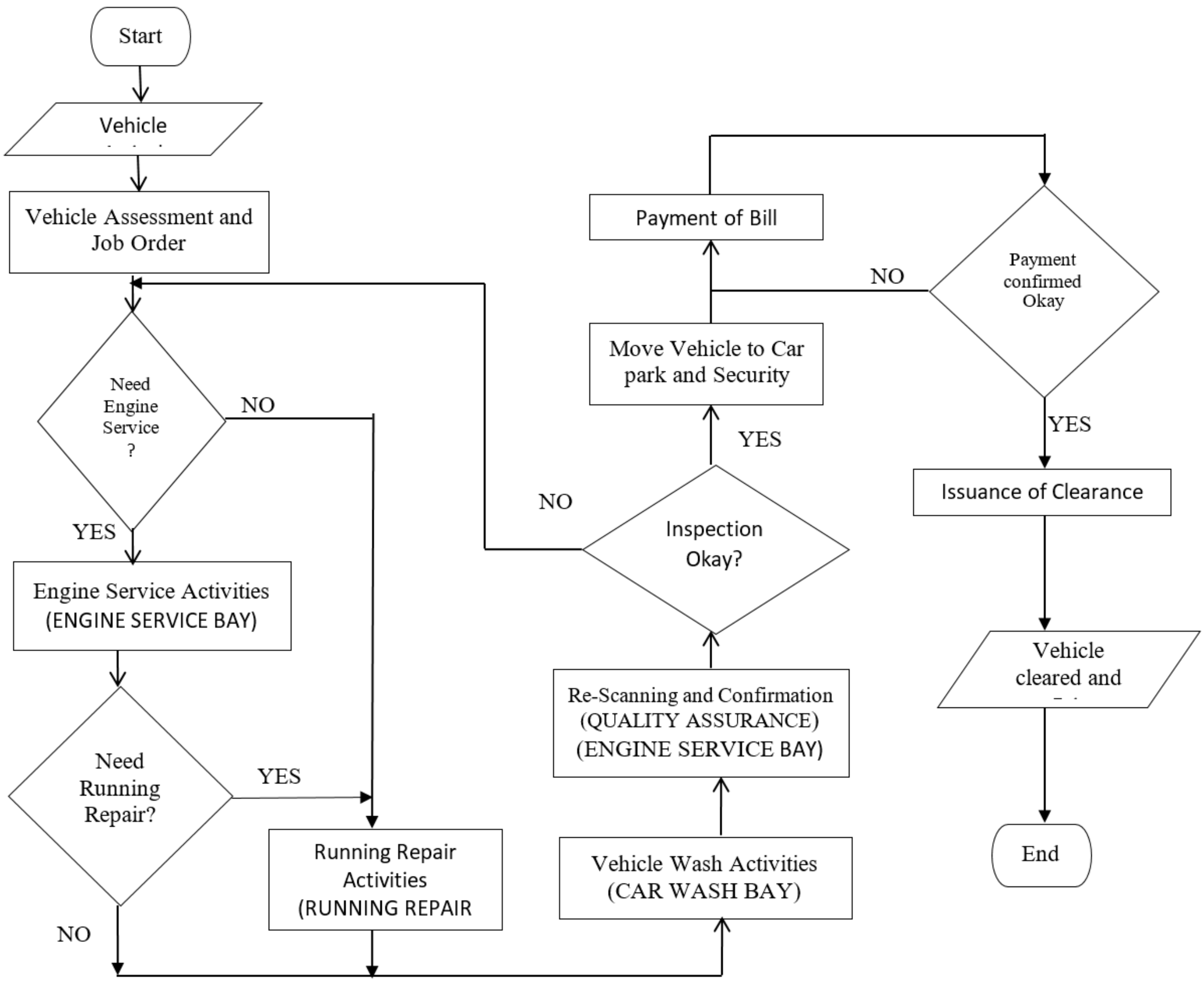

Figure 2: Flowchart of the Developed Automobile Maintenance Service Model

Table 1: Frequency of Vehicles' Arrival and Service in the Centre

`SN	Day/ Date of Arrival	car arrived at the Engine Service Bay					Number of Car(s) arrived	Number of Served Car	Number of left over car	effective working hours
		1	2	3	4	5				
1	Tuesday, January 2, 2024	8	12	11	7	9	47	39	8	9
2	Wednesday, January 3, 2024	10	9	13	8	8	48	42	6	9
3	Thursday, January 4, 2024	12	8	11	9	10	50	45	5	9
4	Friday, January 5, 2024	8	6	9	11	7	41	41	0	9
5	Saturday, January 6, 2024	6	4	5	6	4	25	25	0	5
6	Monday, January 8, 2024	8	7	9	5	11	40	39	1	9
7	Tuesday, January 9, 2024	11	10	10	9	8	48	44	4	9
8	Wednesday, January 10, 2024	9	11	10	8	9	47	45	2	9

9	Thursday, January 11, 2024	10	10	8	9	7	44	44	0	9
10	Friday, January 12, 2024	8	8	8	7	8	39	39	0	9
11	Saturday, January 13, 2024	7	6	5	5	4	27	26	1	5
12	Monday, January 15, 2024	9	11	8	12	10	50	43	8	9
13	Tuesday, January 16, 2024	9	10	10	7	8	44	43	1	9
14	Wednesday, January 17, 2024	11	8	10	8	9	46	42	4	9
15	Thursday, January 18, 2024	10	9	10	9	9	47	44	3	9
16	Friday, January 19, 2024	9	7	8	8	6	38	38	0	9
17	Saturday, January 20, 2024	6	5	5	4	4	24	22	2	5
18	Monday, January 22, 2024	10	8	11	6	9	44	44	0	9
19	Tuesday, January 23, 2024	8	9	10	9	8	44	43	1	9
20	Wednesday, January 24, 2024	10	10	10	8	8	46	42	4	9
21	Thursday, January 25, 2024	8	9	8	8	7	40	40	0	9
22	Friday, January 26, 2024	10	8	7	10	7	42	41	1	9
23	Saturday, January 27 2024	5	5	5	4	4	23	20	3	5
24	Monday, January 29, 2024	10	10	8	6	8	42	42	0	9
25	Tuesday, January 30, 2024	12	12	8	10	9	51	43	8	9
26	Wednesday, January 31, 2024	10	10	10	10	12	52	43	9	9
27	Thursday, February 1, 2024	8	9	8	8	6	39	39	0	9
28	Friday, February 2, 2024	10	8	9	7	7	41	40	1	9
29	Saturday, February 3, 2024	7	6	5	5	4	27	26	1	5
30	Monday, February 5, 2024	8	7	10	9	10	44	43	1	9
	Count	267	252	259	232	230	1240	1167	74	250

Table 2: Vehicle Distributions According to Service Required with Inter Service Queue Network

SN	Day/ Date of Arrived	N0 of Car(s) arrived	N0 of Served car	Engine Service only	Engine Service and Brake Pad	Engine Service and Align-ment	Engine Service and Alterna-tor	Average Queue Network Time (Minutes)	Wor-king Hours
1	Tuesday, January 2, 2024	47	39	29	4	6	0	54.2825	9
2	Wednesday, January 3, 2024	48	42	38	1	1	1	48.2233	9
3	Thursday, January 4, 2024	50	45	40	1	3	1	63	9
4	Friday, January 5, 2024	41	41	41	0	0	0	0	9
5	Saturday, January 6, 2024	25	25	21	2	2	0	30	5
6	Monday, January 8, 2024	40	39	38	0	1	0	65.483	9
7	Tuesday, January 9, 2024	48	44	33	6	3	2	41.24	9
8	Wednesday, January 10, 2024	47	45	41	0	4	0	55.05	9
9	Thursday, January 11, 2024	44	44	44	0	0	0	0	9
10	Friday, January 12, 2024	39	39	34	2	3	1	72.111	9
11	Saturday, January 13, 2024	27	26	25	1	0	0	50	5
12	Monday, January 15, 2024	50	43	38	3	2	0	58	9
13	Tuesday, January 16, 2024	44	43	40	0	2	1	63.8888	9
14	Wednesday, January 17, 2024	46	42	30	2	7	3	48.2222	9
15	Thursday, January 18, 2024	47	44	39	3	1	1	36	9
16	Friday, January 19, 2024	38	38	38	0	0	0	0	9
17	Saturday, January 20, 2024	24	22	15	2	4	1	50	5
18	Monday, January 22, 2024	44	44	36	4	2	2	43.2222	9
19	Tuesday, January 23, 2024	44	43	40	0	3	0	40	9
20	Wednesday, January 24, 2024	46	42	39	0	3	0	36	9

21	Thursday, January 25, 2024	40	40	40	0	0	0	0	9
22	Friday, January 26, 2024	42	41	35	2	2	2	49.6633	9
23	Saturday, January 27 2024	23	20	12	3	4	1	58	5
24	Monday, January 29, 2024	42	42	30	4	6	2	52.042	9
25	Tuesday, January 30, 2024	51	43	38	2	1	2	41	9
26	Wednesday, January 31, 2024	52	43	41	0	0	2	33.8822	9
27	Thursday, February 1, 2024	39	39	39	0	0	0	0	9
28	Friday, February 2, 2024	41	40	40	0	0	0	0	9
29	Saturday, February 3, 2024	27	26	20	1	3	2	42.5622	5
30	Monday, February 5, 2024	44	43	35	2	4	2	47.8888	9
	Count	1240	1167	1029	45	67	26	1179.762	250

Table 3: Service Time of Each Stage in Engine Service Operation

Process	**Minimum Processing Time in** Minutes	**Maximum Processing Time in** Minutes
Scanning and Estimate Approval	15	25
Detachment of Battery Head	1	2
Oil Drain and removal of oil filter	4	8
Dropping of oil	2	5
Insertion of fresh oil and tightening of oil filter	8	12
Tight Battery head	2	4
Start the and run the Ignition	3	5
Rescan and check other parameter	8	15
Car wash	20	25
Send vehicle to Reception	1	2
Quality control		
• Inspection of the vehicle	20	30
• Send vehicle to reception	3	5
• Cashier payment and payment confirmation	25	30
Reception clearance and security pass	8	12
Total	120	180

Table 4: Service Time of Each Stage in Running Repair (Change Break Pad)

Process	**Minimum Processing Time in Minutes**	**Maximum Processing Time in Minutes**
Inspection of the Break system (Determine the need for replacement)	5	15
Removal of the wheel to access the brake components	8	15
Loosen the caliper bolts with a torque wrench and carefully remove the caliper	5	15
Take out the old brake pads and rotors	4	10
Install new rotors and brake pads ensuring proper alignment and secure fastening	8	15

Bleed the brakes to remove air from the system	15	20
Total	45	90

Table 5. Summary of analysed input parameters used for the development of the Hierarchical Timed Coloured Petri Net (HTCPN) model for the automobile maintenance service centre.

Model Input Parameter	Data Analysis Procedure	Result/Output	Use in HTCPN Model
Vehicle arrival rate	Daily vehicle arrivals were divided by daily operating hours (9 hours on weekdays and 5 hours on Saturdays). Monthly average arrival rate was obtained by dividing total monthly arrivals by total operational hours.	Daily average arrival rate varied across observation days. Monthly average arrival rate was **4.96 vehicles/hour** (1,240 vehicles over 250 operational hours).	Used to define the vehicle generation (arrival) process in the simulation model.
Queue network time between service sections	Waiting times between Engine Service and subsequent Running Repair operations (Brake, Alignment, or Alternator Replacement) were summed and averaged for vehicles requiring multiple operations. Monthly average was obtained from the daily averages.	Example: Day 1 average queue network time = **54.28 minutes**. Monthly average queue network time = **39.33 minutes**.	Used to model inter-service waiting delays between maintenance sections.
Engine service processing time	Minimum and maximum processing times were collected from the service centre. Mean time was calculated as the average of minimum and maximum values, producing a triangular distribution.	Processing times represented as Triangular (Minimum, Mean, Maximum) distributions. Example: Scanning and estimate approval = **(15, 20, 25) minutes**.	Used as timed transition parameters for engine service activities.
Brake repair processing time	Minimum, mean, and maximum processing times were determined using the triangular distribution approach.	Example: Brake inspection = **(5, 10, 15) minutes**.	Used to parameterize brake repair transitions in the HTCPN model.
Alternator replacement processing time	Minimum and maximum values were used to compute mean processing time, forming triangular distributions.	Example: Scanning and initial inspection = **(10, 15, 20) minutes**.	Used as timed transition parameters for alternator replacement activities.
Wheel alignment processing time	Processing times were analysed using the same triangular distribution approach.	Example: Suspension and steering inspection = **(5, 7.5, 10) minutes**.	Used to model wheel alignment service operations in the HTCPN model.
Probability distribution	Mean processing time calculated as (Minimum + Maximum)/2 for each	Triangular distribution (Minimum, Mean,	Provides stochastic service times within the

adopted	activity.	Maximum) adopted for all service operations.	simulation model.

Development of the HTCPN Model

The developed HTCPN model comprises five principal modelling components: places, transitions, colour sets, variables, and functions (Table 6). Places represent vehicle states, resource availability, and operational conditions, whereas transitions model maintenance activities and decision points. Colour sets define the data structures for vehicles, workers, queues, and processing states, while variables facilitate token manipulation during transition firing. User-defined functions initialize system resources, generate vehicle arrivals, and model service and simulation times. Together, these components provide the formal structure required to represent the operational behaviour of the automobile maintenance service centre.

The automobile maintenance service centre was modelled using a Hierarchical Timed Coloured Petri Net (HTCPN) to provide a formal, modular, and executable representation of the service workflow. The model was designed hierarchically to capture the complexity of maintenance operations while maintaining clarity and scalability. It comprised four interconnected modules: Car Park and Security, Information Desk, Workshop/Operation, and Quality Assurance, with each module representing a distinct stage of the maintenance process. The developed interconnected modules are represented by Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, and Figure 8 respectively.

Table 6: Summary of the developed HTCPN Model Components

HTCPN Component	Description	Representative Elements
Places	Represent vehicle states, queues, resources, and operational conditions throughout the maintenance process.	Vehicle Arrival, Vehicle Queue, Information Desk, Vehicle Examination, General Service, Departure
Transitions	Represent maintenance and administrative activities that change vehicle states.	Vehicle Arrival, Vehicle Registration, Information Desk, Vehicle Examination, Servicing Section
Colour Sets	Define data types for modelling vehicles, personnel, queues, and processing states.	Vehicle type, Worker type, Queue, Processing state, Integer, Real
Variables	Enable movement and manipulation of coloured tokens during transition firing.	Vehicle, Queue, Worker, Integer, Processing state
Functions	Initialize resources and model system dynamics such as arrivals, service times, and simulation time.	Arrival time, Simulation time, Officer initialization, Technician initialization, Quality officer initialization

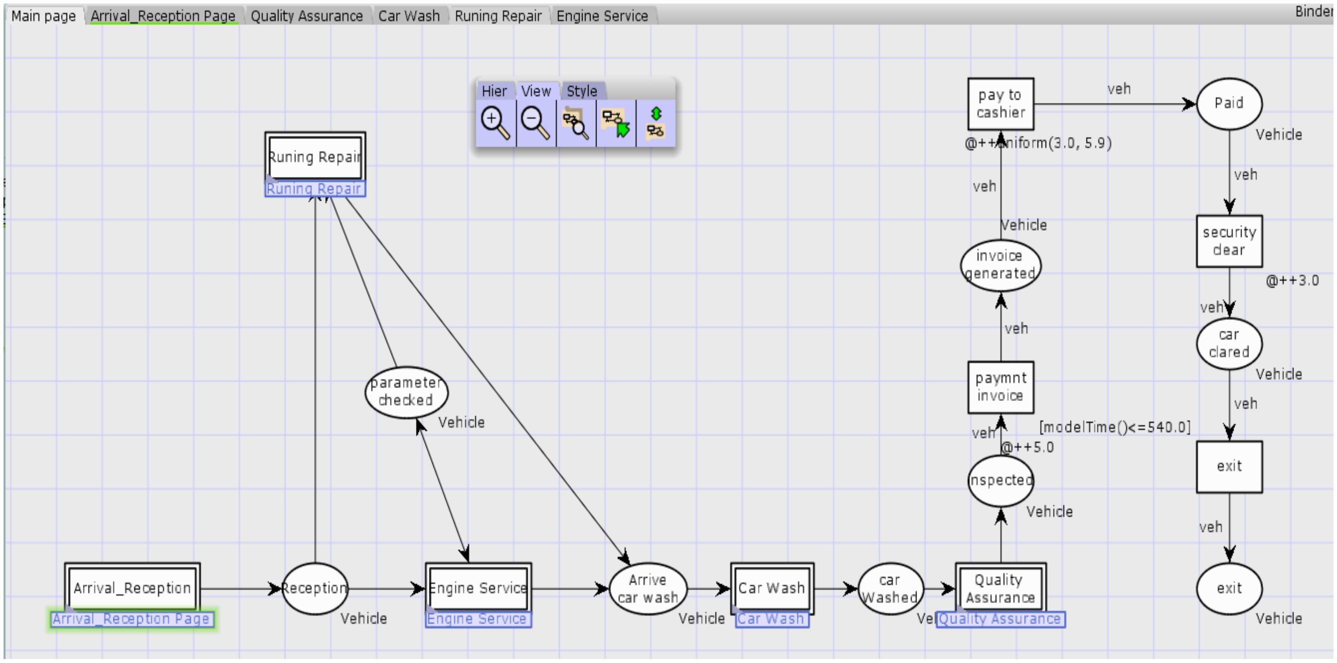

Figure 3: The Developed HTCPN model for Automobile Maintenance Service Centre flow processes

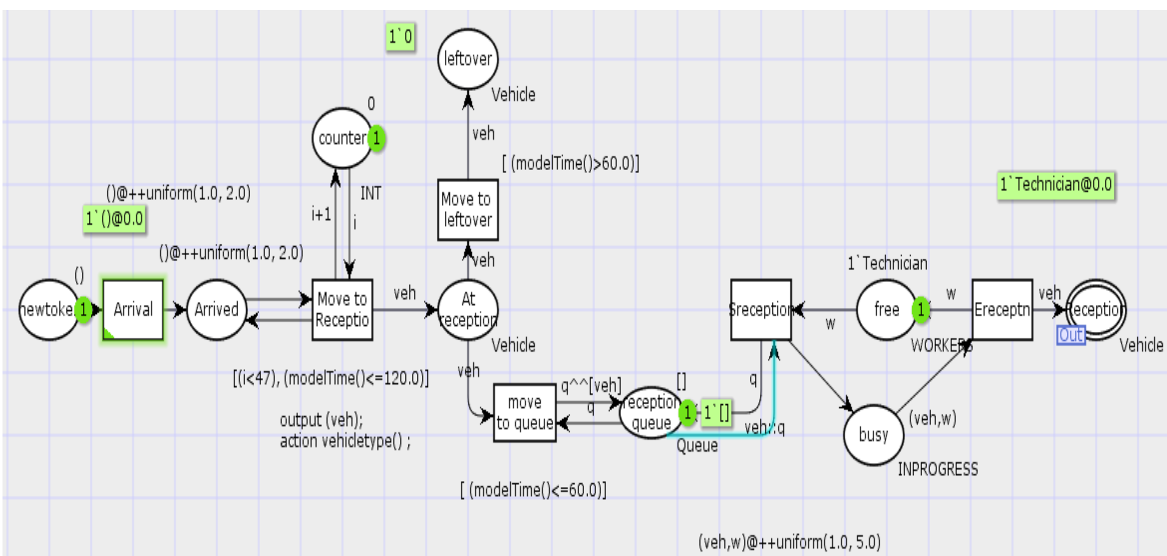

Figure 4: The Arrival-Reception module of the Developed HTCPN Model

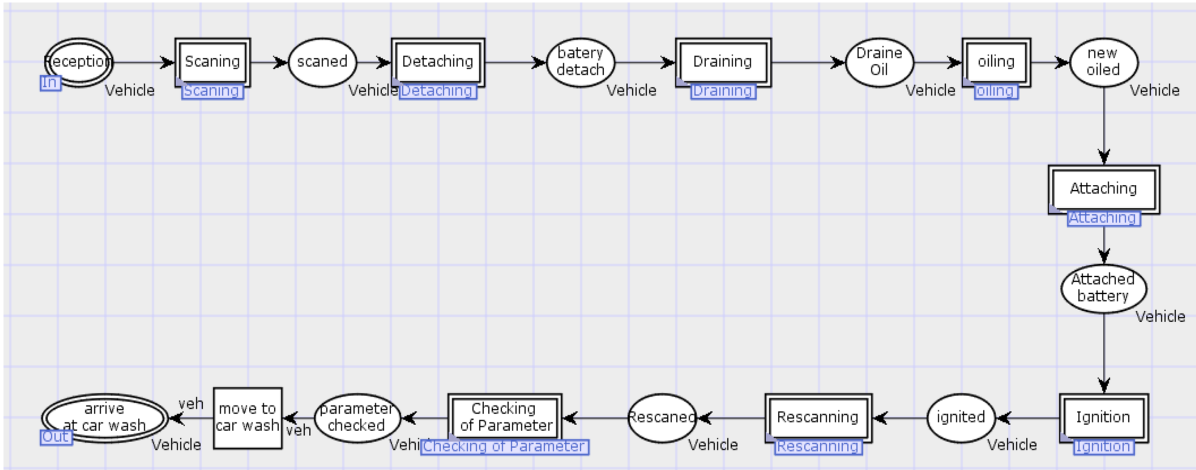

Figure 5: The Engine Service Module of the Developed HTCPN Model

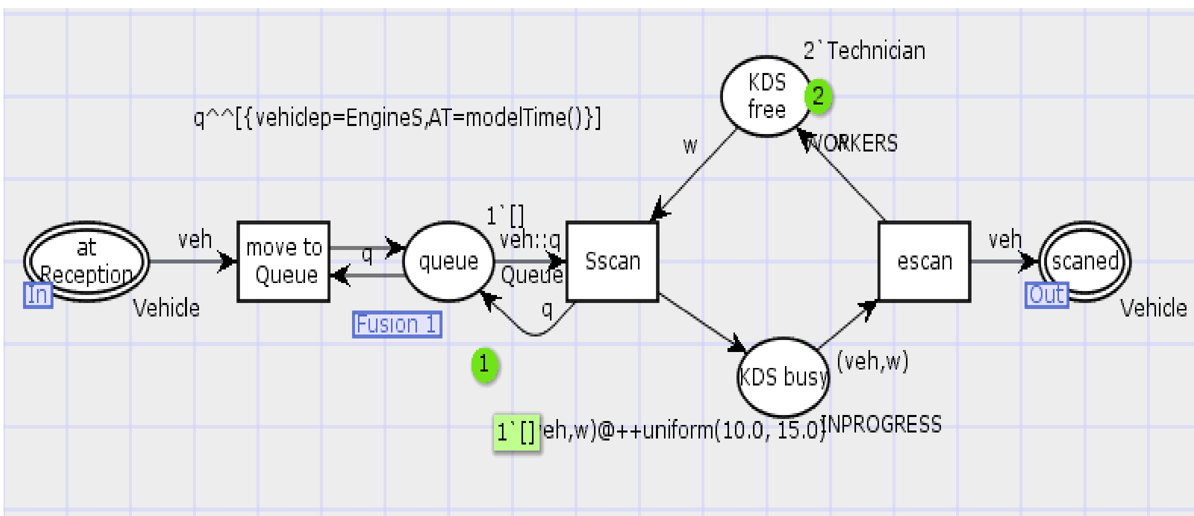

Figure 5 (a): The Scanning Sub-module of Engine Service Module of the Developed HTCPN Model

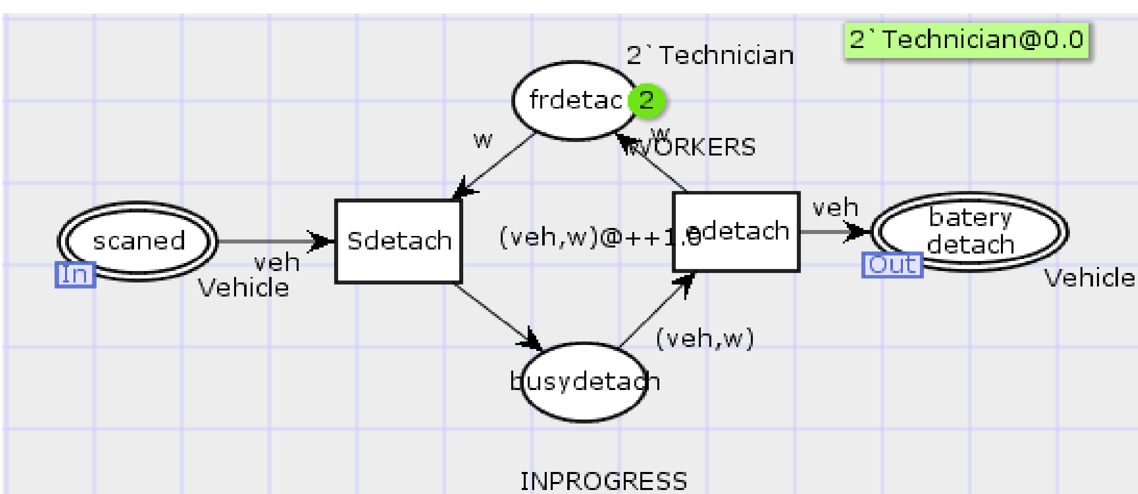

Figure 5 (b): The Detach Battery Sub-module of Engine Service Module of the Developed HTCPN Model

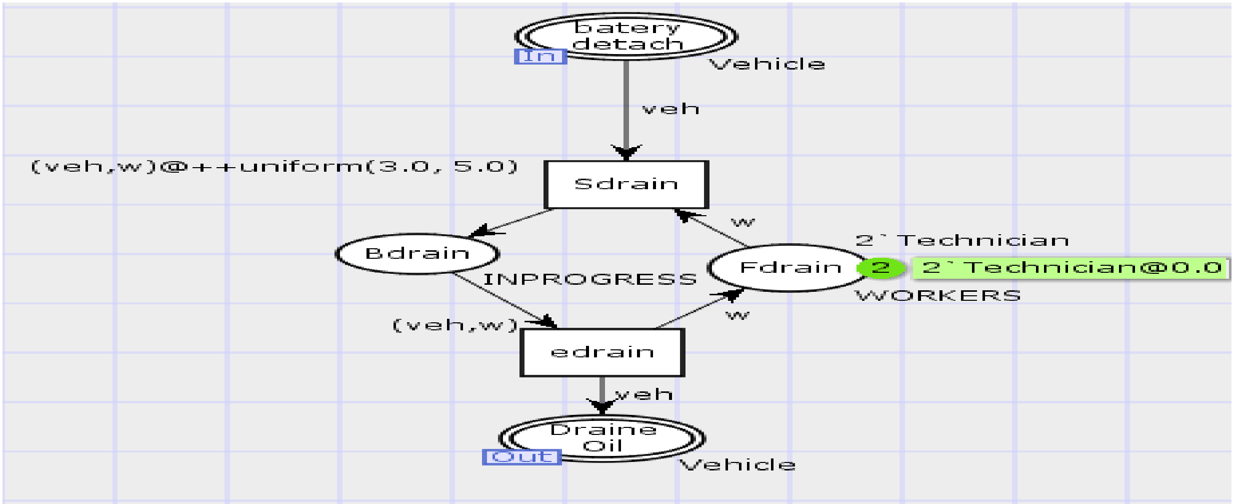

Figure 5 (c): The Drain Oil Sub-module of Engine Service Module of the Developed HTCPN Model

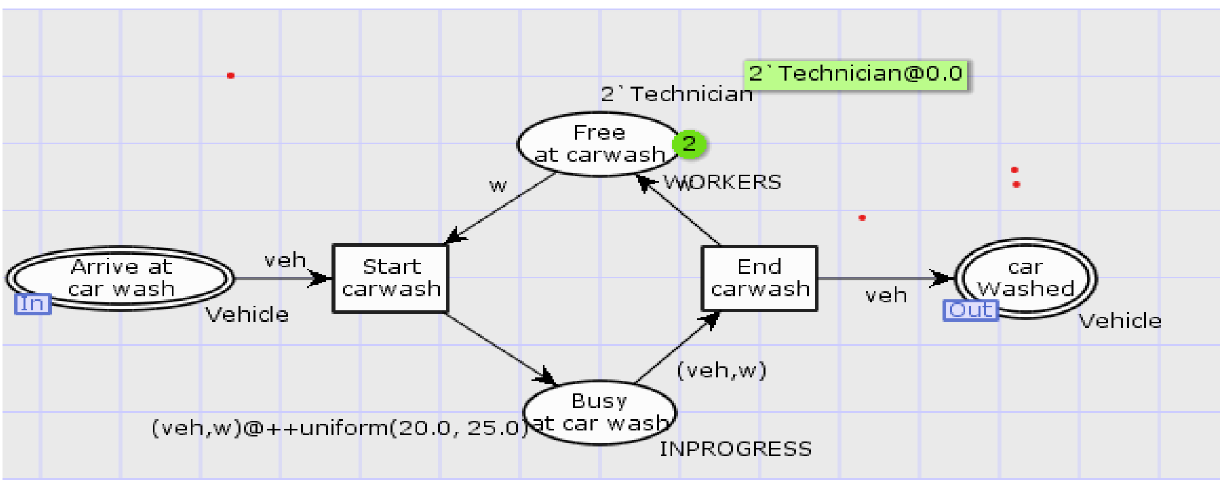

Figure 6: Car Wash Module of the Developed HTCPN Model

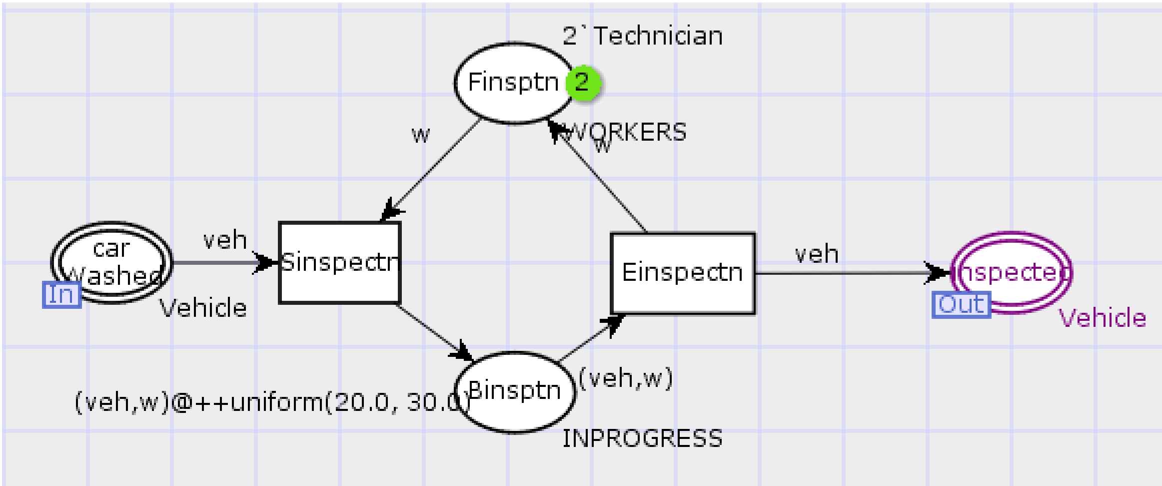

Figure 7: Quality Control/Assurance Module of the Developed HTCPN Model

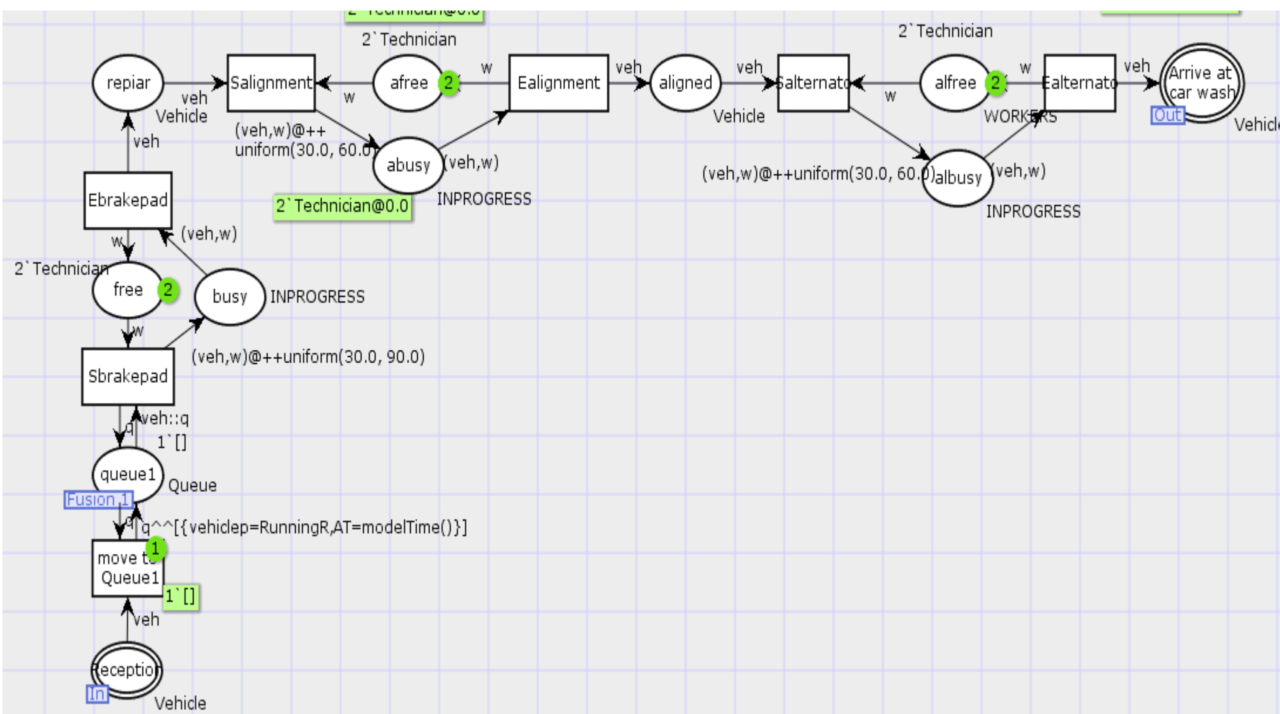

Figure 8: Running Repair Module of the Developed HTCPN Model

MODEL VERIFICATION

Model verification was performed to confirm that the developed Hierarchical Timed Coloured Petri Net (HTCPN) accurately implemented the operational logic of the automobile maintenance service centre and was free from structural and behavioural errors prior to simulation. The model was implemented in CPN Tools, where syntax and semantic checks verified the correctness of colour sets, variables, arc inscriptions, timing expressions, guard functions, and hierarchical substitution transitions. The model compiled successfully without errors, confirming the correctness of its implementation.

State-space analysis confirmed that all operational states were reachable from the initial marking and that no unintended deadlocks existed. The only dead markings corresponded to legitimate termination states after all vehicles had completed their maintenance operations. The analysis further showed that all places remained bounded, preventing uncontrolled token accumulation, and that all transitions were live, indicating that every maintenance activity could eventually be executed whenever its enabling conditions were satisfied. Token conservation was also verified, confirming that vehicle tokens were neither duplicated nor lost during execution.

In addition, verification of the hierarchical structure confirmed correct synchronization and information exchange between the top-level model and subordinate service modules through substitution transitions. Collectively, these results demonstrate that the developed HTCPN satisfies the fundamental structural and behavioural properties required for discrete-event simulation and is suitable for subsequent performance evaluation and what-if analyses. A summary of the verification results is presented in Table 7**.**

Table 7. Summary of HTCPN Model Verification Results

Verification Property	Verification Method	Result	Interpretation
Syntax correctness	CPN Tools syntax checker	Passed	Model declarations and inscriptions are correctly defined.
Hierarchical consistency	Verification of substitution transitions	Passed	Top-level and subpage modules communicate correctly.
Interactive simulation	Token-flow observation	Passed	Vehicle tokens followed the intended maintenance workflow.
Reachability	State-space analysis	Passed	All maintenance states are reachable from the initial marking.
Deadlock freedom	State-space analysis	Passed	No unintended deadlocks; termination occurs only after all vehicles complete service.
Boundedness	State-space analysis	Passed	All places remain bounded throughout execution.
Liveness	State-space analysis	Passed	All service transitions remain executable when enabled.
Token conservation	Simulation and state-space analysis	Passed	Vehicle tokens are neither duplicated nor lost.
Timing consistency	Timed simulation	Passed	Transition firing delays conform to specified triangular processing-time distributions.
Overall verification	Combined verification procedures	Success ful	The HTCPN model is logically correct and suitable for simulation-based performance analysis.

Conclusion

The study presented the development of a Hierarchical Timed Coloured Petri Net (HTCPN) model for an automobile maintenance service centre to support the modelling, analysis, and simulation of maintenance service operations. Operational data collected from the case study were analysed to determine vehicle arrival rates, queue network times, and service processing times, which served as input parameters for the model. The hierarchical structure of the HTCPN enabled the decomposition of the maintenance system into manageable service modules, including engine service, brake repair, alternator replacement, and wheel alignment, while preserving the interactions and synchronization among the different maintenance activities.

The developed HTCPN model provides a formal representation of the maintenance workflow by integrating concurrency, resource sharing, timing constraints, and stochastic service processes within a unified modelling framework. Model verification confirmed the correctness of the implementation through syntax checking, interactive simulation, and state-space analysis. The verification results demonstrated that the model was free from structural and behavioural inconsistencies, exhibiting desirable properties such as reachability, boundedness, liveness, token conservation, and the absence of unintended deadlocks.

The study demonstrates that HTCPN is an effective modelling technique for representing the dynamic behaviour of automobile maintenance service centres. The model provides a reliable platform for analysing system performance, identifying operational bottlenecks, evaluating resource utilization, and supporting evidence-based decision-making. Furthermore, the modular nature of the hierarchical model facilitates future system modifications and scalability without requiring extensive redesign of the entire maintenance process. Consequently, the developed HTCPN model constitutes a practical decision-support tool for improving operational efficiency and service delivery within automobile maintenance service centres.

Future research should extend the developed HTCPN model through comprehensive simulation-based performance analysis using real operational data collected over observation periods from automobile maintenance service centres. Different operational scenarios, including variations in staffing levels, service bay capacity, vehicle arrival rates, service scheduling policies, and resource allocation strategies, should be investigated to identify optimal operating conditions. Such scenario-based analyses would enable the evaluation of key performance indicators, including vehicle waiting time, service time, queue length, throughput, and resource utilization, thereby supporting evidence-based decision-making for continuous improvement of maintenance operations. Furthermore, the model may be integrated with optimization techniques, artificial intelligence, or machine learning methods to develop intelligent decision-support systems capable of enhancing the efficiency, responsiveness, and sustainability of modern automobile maintenance service centres.

References

Abbes, S., Hassine, H., Chaari,R. Amari, S. and Haddar M. (2025). Modular management and analysis of predictive aircraft maintenance using coloured Petri nets. SogeJournal: 240 (1)

Alsyouf, I., Alsuwaidi, M., Hamdan, S., and Shamsuzzaman, M. (2022). A framework for maintenance management and performance improvement using Industry 4.0 technologies. Journal of Quality in Maintenance Engineering, 28(4), 879–900. https://doi.org/10.1108/JQME-08-2021-0065

Badmus, T. A., Remenyte-Prescott, R. and Prescott, D. (2025). A novel fault detection and diagnostic Petri net methodology for dynamic systems using Petri nets. 239(1): https://doi.org/10.1177/1748006X231212539

Dehantoro, J., Sumiardi, D. and Hijuzaman, O. (2016).Analysis of Vehicle Service Queuing System Using Arena in Authorized Workshop. International Journal of Science and Research (IJSR) ISSN (Online): 2319-7064. 5(5) CPN2000 Project. Online: http://www.daimi.au.dk/CPnets/CPN2000/

Gehlot, V. (2019). From Petri nets to Colored Petri Nets: A tutorial introduction to nets-based formalism for modeling and simulation. Proceedings of the Winter Simulation Conference, 1519–1533. https://doi.org/10.1109/WSC40007.2019.9004691

Huang, H. Z. and Zu, X (2025). Hierarchical Timed Coloured Petri Nets Based Product Development process Modelling. In: Shen et al (eds), CSCCD 2004, LNCS 3168, springer, pp 378-387

James, A.T., Kumar, G., Bhalla, M., Amar, M. and Jain, P. (2020), "Analysis of challenges for automobile service garages in India: a structural modelling approach", Journal of Advances in Management Research, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/JAMR-04-2020-0059. Emerald Publishing Limited

James, A. T., Kumar, G., James, J., and Asjad, M. (2023). Development of a micro-level circular economy performance measurement framework for automobile maintenance garages. Journal of Cleaner Production, 417, 138025. https://doi.org/10.1016/j.jclepro.2023.138025

Jensen, K., and Kristensen, L. M. (2009). Coloured Petri Nets: Modelling and Validation of Concurrent Systems. Springer.

Jensen, K., and Kristensen, L. M. (2015). Colored Petri nets: A graphical language for formal modeling and validation of concurrent systems. *Communications of the ACM*, *58*(6), 61–70. https://doi.org/10.1145/2663340

Kaid, H., Al-Ahmari, A., and Alqahtani, K. N. (2023). Fault detection, diagnostics, and treatment in automated manufacturing systems using Internet of Things and Colored Petri Nets. Machines, 11(2), 173. https://doi.org/10.3390/machines11020173

Kwakye, A. D., Jennions, I. K., and Ezhilarasu, C. M. (2024). Platform health management for aircraft maintenance: A review. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 238(3). https://doi.org/10.1177/09544100231219736

Li, X., Wang, Y., Zhang, H., and Zhao, J. (2024). Discrete-event simulation for service operation optimization in maintenance systems: A review. Reliability Engineering & System Safety, 245, 110013. https://doi.org/10.1016/j.ress.2024.110013

Liu, F., and Zhang, H. (2018). A class of extended time Petri nets for modeling and simulation of discrete event systems. Simulation, 94(8), 753–762. https://doi.org/10.1177/0037549717742716

Mehdi, I., Boudi E. M., and Mehdi A. M. (2024). Reliability, Availability, and Maintainability Assessment using Timed Coloured Petri Nets. MDPI: 14(11), 4852; https://doi.org/10.3390/app14114852

Nguyen, T. T., Le, H. T., and Pham, D. T. (2023). Intelligent maintenance strategies for smart manufacturing: A review. Journal of Manufacturing Systems, 69, 280–299. https://doi.org/10.1016/j.jmsy.2023.05.012

Orlov, S. P., Susarev, S. V., & Uchaikin, R. A. (2021). Application of hierarchical colored Petri Nets for technological facilities' maintenance process evaluation. Applied Sciences, 11(11), 5100. https://doi.org/10.3390/app11115100

Sharma, D., Yadav, V., and Singh, D. (2023). Advancements and implications of product service systems in the automobile industry: A comprehensive review. Engineering Proceedings, 59(1), 98. https://doi.org/10.3390/engproc2023059098

Wang, M., Dong, F., Men, F., & Li, J. (2023). Research on process simulation based on random Petri Nets: Taking the after-sales maintenance process of automobiles as an example. In Proceedings of the International Conference on Engineering Management. Atlantis Press. https://doi.org/10.2991/978-94-6463-308-5_26

Yadav, G., et al. (2023). Development of a micro-level circular economy performance measurement framework for automobile maintenance garages. Journal of Cleaner Production, 417, 138025. https://doi.org/10.1016/j.jclepro.2023.138025.