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Research on Process Simulation Based on Random Petri Nets--Taking the after-sales maintenance process of automobiles as an example

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Abstract. In the context of the digital economy, business processes are constantly changing, increasing the difficulty of enterprise management and increasing operational risks. This article combines random Petri nets and takes after-sales maintenance scenarios as an example to analyze the current status of after-sales maintenance processes in a certain 4S store. A maintenance process model based on Petri nets is established, and the process effectiveness is quantitatively studied through assignment. This research applies the Petri net theory to the specific business processes of the automotive industry, enriching the Digital transformation process simulation tool library.

Keywords: Random Petri Nets; Process simulation; Automobile after-sales maintenance

1 Introduction

Process is the process of creating enterprise value, but traditional business processes have many pain points such as fragmentation, redundancy, and complexity, forming information islands and data islands, which hinder the innovative development of enterprises. In the context of the digital economy, with the continuous advancement of the enterprise's Digital transformation process, it has become a general trend to go deep into business scenarios and design business flows from the perspective of full process and full scene user experience, and enterprise business processes are constantly reshaped. As Huawei experts said, "The essence of Digital transformation is business transformation and value chain remodeling. The priority of Digital transformation is process reconstruction, that is, business process". In the wave of Digital transformation, the normalization and transformation of processes become inevitable. In order to reduce the risks of process change and improve the stability of process change, it is necessary to conduct a quantitative evaluation of the effectiveness of process change in advance, identify the overall performance of the process and identify breakpoints and blockages.

Considering the strong correlation between scenario operational efficiency and process optimization, this article uses process optimization related theories as the

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basis for studying. Scholars have conducted extensive research on process optimization. In terms of business process optimization theory, Chen Huiling et al. [1] modeled the purchase transaction using Petri nets and analyzed the time function of the model. Liu Hang et al. [2] analyzed outpatient problems based on Petri nets to improve the efficiency of the outpatient process. Ren Ning[5] applied the theory and method of business process reengineering to procurement business examples and proposed solutions for process optimization; Wang Meilan[7] combined the theories of value chain and business processes to optimize and improve the main activities of value creation for BW enterprises, and proposed effectiveness evaluation and guarantee measures; Zhu Jingduo[8] optimized the product certification process by combining causal diagrams, 5W1H, ECRS, and other methods; Zhu Fanfan[9] introduced TOC constraint theory and project management theory into the field of business process management; Yang Haiyan et al.[6] proposed a project management process optimization plan based on the ESIA method, starting from a series of problems in project management. In terms of business process modeling, You Jianxin et al.[11] used the IDEFO method to describe enterprise business processes, analyzed the problems in the processes using the FEMA method, and optimized enterprise processes using Pareto's law and other methods; Starting from the limitations of static analysis methods such as BPR, IDEF, and ARIS models, Liu Juan[10] introduced Petri nets, a dynamic modeling and analysis method, into the field of process optimization to optimize and analyze the inbound and outbound processes.

This article is based on the complex discrete manufacturing industry - the automotive industry. Taking the automotive after-sales maintenance process as an example, it systematically reviews the process simulation methods based on Petri nets, in order to provide a basic reference for enterprise process governance in the digital context.

2 Related theories

2.1 Petri Net Definition

Petri net is a modeling tool that uses certain symbols to describe models and is often used for process modeling. It can provide a powerful means for describing and studying information processing systems with characteristics such as parallelism, asynchrony, and randomness [3]. Therefore, Petri nets are more in line with the characteristics of business processes in the automotive industry and can better describe the connections and relationships between various process links.

The basic Petri net has a simple structure, mainly consisting of elements such as place (P), transition (T), connection (C), and token (T). The repository represents the position and state of the system, while transition refers to the consumption, use, and generation of resources in the system. connections are usually represented by a directed line segment in the model, while Token is usually represented by a black dot in the model, which can move between two repositories. The number represents the number of resources in the repository.

If a seven tuple $\sum = (P, T, F, W, K, M_0, \lambda)$ is defined as a random Petri net, the element definition and connotation are as follows:

$P = (p_1, p_2, \text{L}, p_m)$ is a set of finite repositories;

$T = (t_1, t_2, \text{L}, t_n)$ is a set of finite transitions;

$P \cap T = \phi$ means that set P and the set T do not intersect;

$P \cup T \neq \phi$ means that the set P and the set T are different, they are empty sets;

$F \subseteq (P \times T) \cup (T \times P)$ (X is a Cartesian product), which means that the relationship F only exists between the set P and the set T, which is a connection set;

$W : F \rightarrow \{1,2,\text{L}\}$ (relation set F is a mapping to a positive integer) is a directed weight function;

$K : P \rightarrow \{1,2,\text{L}\}$ (mapping of set P to positive integers) is the capacity function of the library;

$M_0 : P \rightarrow \{1,2,\text{L}\}$ (the mapping of set P to natural numbers) is the initial identifier.

$\lambda = \{\lambda_1, \lambda_2, \lambda_3, \text{L}\, \lambda_n\}$ is the set of average implementation rates of transitions. λ_i represents the average implementation rate of the transition, and X represents the number of implementation times per unit time. $r_i = 1/\lambda_i$ is the reciprocal of the average implementation rate, and λ_i represents the average implementation delay of the transition. The following figure shows a Petri net with 2 repositories and 1 transition.

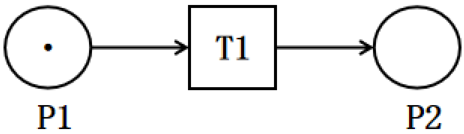

Fig. 1. Petri net model.

2.2 Performance Analysis of Random Petri Nets

The performance analysis of stochastic Petri nets generally follows the following process:

(1) Construct a process Petri net and conduct reliability analysis on it.

(2) Set transition delay. Based on the established model, associate all transitions with a delay that matches the actual situation.

(3) Isomorphic Markov chains. Based on the known stochastic Petri net model, a Markov chain is isomorphically obtained based on the distribution of Tokens (resources) in the model repository and the triggering rules of transitions in the model.

(4) Solve Markov processes. Based on the obtained Markov chain, the transfer rate matrix of Markov process is constructed, and the steady-state probability is obtained by solving the matrix equation.

Suppose that a Markov chain with the same structure as the stochastic Petri net already exists, and the Markov chain has n states, then the transition rate matrix Q can be defined as:

$$Q = \lfloor q_{\mathrm{i,j}} \rfloor, 1 \le i, j \le n$$

The element $q_{\mathrm{i,j}}$ value of the transfer rate matrix is: when an element on the diagonal of matrix $q_{\mathrm{i,j}}$ is present, its value is equal to the opposite of the sum of the rates marked on each arc outputting from state $\mathrm{m_i}$ to all other states $\mathrm{m_j}$; If it is not an element on the diagonal of matrix $q_{\mathrm{i,j}}$, determine whether the state identifiers $\mathrm{m_i}$ and $\mathrm{m_j}$ are connected by an arc. If so, the value marked on the arc is the value of $q_{\mathrm{i,j}}$. If not, it is 0.

Let the steady-state probability of n states in the Markov chain be a row vector $\mathrm{X} = (\mathrm{x_1}, \mathrm{x_2}, \mathrm{L}, \mathrm{x_n})$, and from the properties of the Markov chain, we can get the equations:

$$\begin{cases} XQ = 0 \\ \sum_{\mathrm{i}} x_i = 1 \end{cases}$$

By solving this system of equations, the steady-state probability $P[M_{\mathrm{i}}] = x_i (1 \le i \le n)$ of reachable identification can be obtained.

(5) Quantify the effectiveness of process operation. Determine the final performance estimate required for the entire system described by the model through the calculation of the final performance indicators.

Let $\overline{u_i}$ be the average number of markers in any reachable marker for position s_i under steady-state conditions, and $\overline{U_i}$ be the average number of markers for position set S_j. The average number of tags in the position represents the length of the task queue and is an important indicator used to analyze the response time and throughput capacity of the subsystem. $R(\mathrm{t}, s)$ is the marker flow rate, which is the average number of markers flowing into the post position s of t within a unit time, and λ is the average implementation rate of t. According to the principle of equal entry and exit rates of the system, the average delay time of the system is the quotient of the average number of tags contained in the system location set and the average tag flow rate flowing into the subsystem.

$$\overline{u_i} = \sum_j j \times P[M(s_i) = j]$$

$$\overline{U_i} = \Sigma_{\mathrm{s}_i \in \mathrm{S}_j} \overline{\mathrm{u}_i}$$

$$R(\mathrm{t},s) = W(\mathrm{t},s) \times U(t) \times \lambda$$

3 After sales maintenance process model based on Petri nets

3.1 Model building

Under the premise of setting relevant conditions and based on various links in the after-sales service process of automobile 4S stores, a Petri net based after-sales maintenance process model is constructed, as shown in Figure 2. The meaning of the relevant libraries and changes in the figure is shown in Table 1.

To ensure the correctness of the process, reliability analysis is conducted on the constructed process Petri net. The workflow network satisfies the following conditions in structure: 1) After a series of changes in the initial identifier P1, it is certain to reach the end identifier P7; 2) The initial identifier P1 undergoes a series of transitions to reach the end identifier P7, while outputting at least one token in the repository; 3) The workflow network does not contain dead changes. Based on the above conditions, it is determined that the workflow network is reliable.

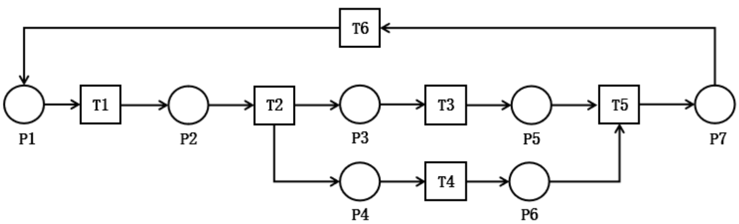

Fig. 2. Petri net model for online after-sales maintenance process.

Table 1. The Meaning of Library Location and Transition in Petri Net Model.

Place	Meaning	Transition	Meaning
P1	Customer enters the appointment interface	T1	Customer repair information filling and acceptance
P2	4s store has received an appointment and is preparing for review	T2	Review and acceptance
P3	4s store completes acceptance and prepares materials	T3	4s store prepares materials
P4	User has successfully made an appointment and is ready to arrive at the store	T4	User arrives at the store and completes identity verification
P5	Material preparation completed, waiting for repair	T5	Repair
P6	Complete identity verification and wait for repair		

When analyzing the performance of workflow models, there are generally two situations: limited resource quantity and unrestricted resource quantity. This study is set as a resource limited situation [4]. Car repair services require time, and due to resource constraints, such as longer time spent, relatively less equipment, and insufficient human resources, car owners may queue up and wait until the previous car owner completes the repair and service resources become available before providing repair services to the next car owner in the queue.

3.2 Performance indicator calculation

Repair waiting time is an important factor that both 4S stores and users are concerned about. This article conducts on-site research on 4S stores and assigns values to the operation time of each link in the process, as shown in Table 2. According to Figure 1, we can get the Markov chain as shown in Figure 3, and the model flag state and inclusion database are shown in Table 3. The transfer rate matrix Q obtained from MC is as follows.

Table 2. Transition assignment situation.

Place	min	Rate	1/min
P1	2	T1	0.5
P2	2	T2	0.5
P3	10	T3	0.1
P4	1	T4	1
P5	40	T5	0.025
P6	10		0.1

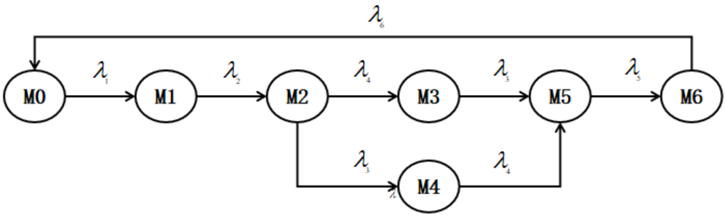

Fig. 3. MC for online after-sales maintenance process.

Table 3. Markov chain correspondence.

Identifying	M0	M1	M2	M3	M4	M5	M6
Place	P1	P2	P3/P4	P3/P6	P4/P5	P5/P6	P7

$$Q=\begin{bmatrix} -0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.5 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1.1 & 1 & 0.1 & 0 & 0 \\ 0 & 0 & 0 & -0.1 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.025 & 0.025 \\ 0.1 & 0 & 0 & 0 & 0 & 0 & -0.1 \end{bmatrix}$$

According to the calculation method of steady-state probability, the stability probabilities of each state are obtained as shown in Table 4. According to the performance indicator calculation method, the average number of Tokens in the system's libraries is 1.7804, and the average labeled flow rate into the system is 0.0155. According to the principle of equal inflow and outflow rates in the system, the average delay time of the system is 114.86 minutes.

Table 4. Stability probability of each state.

Identifying	M0	M1	M2	M3	M4	M5	M6
Pi	0.031	0.031	0.0142	0.142	0.001	0.624	0.157

4 Conclusions

This article introduces Petri nets into the field of process modeling and introduces the basic theory and performance analysis methods of stochastic Petri nets. And apply relevant methods to the automotive after-sales maintenance process, simulate and quantitatively calculate the effectiveness of the process. The basic theory of stochastic Petri nets and performance analysis methods have laid a solid theoretical foundation for process modeling and optimization. This article verifies the usability of this method in the automotive industry, but further research is needed on how to combine process quantification effects for precise transformation of processes.

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