Simulation-Based Multi-Response Optimization for Primary Healthcare System Design and Operation

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Abstract. Primary care physician service is a good form of medical service. Many countries, such as China, are in the early stages of developing family doctor services and need a mature service system. The services residents receive after signing up with a primary care physician must be clarified. In many urban communities in China, universal healthcare policies have emerged. However, most need more resources, and primary care physicians and nurses cannot provide primary care services to all community residents. This study designs a primary health care system involving general practitioners and nurses based on a Chengdu, Sichuan Province community. Moreover, the operation of this primary healthcare system is modeled by a discrete event simulation to find the service capability of the system. Then we design the optimization experiments using Taguchi's method, define multiple factors and corresponding levels, simulate the system operation by simulation model for different combinations of factors and levels, and obtain the corresponding response variables. Finally, we apply the weighted principal component analysis based on multi-response optimization to find the optimal human resource allocation, which provides guidance for better service of the primary health care system.

Keywords: Primary care physician · Discrete event simulation · Taguchi's method · Multi-response optimization

1 Introduction

Due to urban communities' complex health and social needs, urban health systems face many challenges in providing high-quality care to their populations. This situation enormously affects healthcare management, services, and policies [1]. The urban health system must establish comprehensive and practical solutions to those problems [2].

With the change in the medical model, China's medical and health care faces many challenges, such as the high prevalence of chronic diseases, changing disease spectrum, the aging population, and increased medical costs. The medical service model centered

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on disease treatment in large general hospitals can hardly meet the public's demand for continuous and long-term health care. In addition, the concentration of residents in large general hospitals could be more conducive to the balanced allocation of medical resources and the reasonable control of medical costs. Finding a suitable grassroots health service model is imperative to alleviate this phenomenon. The critical link is to improve the level of grassroots medical services, let grassroots medical institutions take on more health services functions, and guide residents to the grassroots medical institutions for the first time [3].

Primary care physicians provide residents with integrated services such as preventive care, treatment of common and frequent diseases, patient rehabilitation, chronic disease management, healthcare management, and primary care at the grassroots level in the primary healthcare system of today's China [4]. Primary healthcare has received considerable attention as part of China's efforts to provide citizens with universal and equitable medical services. China has introduced some policies, such as the Healthy China 2030 Plan, to establish a comprehensive service system based on primary health care to prevent and manage chronic diseases.

However, in today's China, even after contracting, there are cases where it is difficult to fulfill the agreement. For example, the Fangcao Street community in Chengdu, Sichuan Province, is located in the heart of a central city in western China, with over 170,000 permanent residents. It has 25 primary-care physicians for adults and older people, 2 primary-care physicians, especially for children, 2 for maternity, and 60 nurses. Most primary healthcare services in the community are based on an agreement with the hospital. Residents and the hospital provide health care services during the agreement cycle after signing a service agreement with the hospital, depending on the type of service agreement signed and the level of care. However, the current primary healthcare services cover only residents who agree with the hospital, and its coverage is small enough to meet all community residents' primary healthcare needs. Therefore, in this paper, we want to design a new primary care delivery system to meet the healthcare needs of the entire community.

After constructing the new primary care delivery system, we need to test the operational status of the system as well as consider the number of human resources used in the system, which are the number of primary care physicians and nurses and their working hours. Therefore, here we use discrete-event simulation to simulate the system's operation. After the initial simulation of the system, we found that the number of human resources available in the system is low and does not meet the system's operational needs and that many residents do not receive services on time. Therefore, we need to optimize the number of primary care physicians and nurses or their working hours to reduce the residents' waiting time. Here, we used Taguchi's method to design factors, namely the number of primary care physicians and nurses and their working hours and divided each factor into four levels. In addition, we designed three effect variables to evaluate the service indicators of the system. We used the discrete-event simulation system to conduct the experiments and obtain the values of the response variables. Finally, we applied multiple response variable analysis to find the best level combination of the three factors, implying the optimal number of human resources to maintain the operation of this primary care system.

2 Literature Review

Research on the primary care system began early, and several articles have explored the role of primary care and the positive effects of primary care physicians on the improvement of the health status of the population. Based on the data from the Area Resource File (a Health Resources and Services Administration US county-level database), Kravet et al. suggested that if we increase the proportions of primary care physicians, there would be a significant decrease in measures of health care utilization across the 1990s [5]. Starfield et al. collected evidence of the health-promoting influence of primary care to show that primary care helps prevent illness and deaths, which proves the contribution of primary care to the health system [6]. Some scholars have also identified barriers to the implementation of primary care. Carey et al. proposed that the most common obstacles associated with bureaucratic procedures were communication between healthcare professionals, primary care practitioners' commitments, and their skills or confidence in delivering palliative care. Meanwhile, they suggested that an overall approach to overcoming those obstacles should be established [7].

Several scholars have proposed a framework for primary care and analyzed its feasibility based on geography in their studies. Based on the data from Johns Hopkins Community, Berkowitz et al. suggested novel care coordination that contains services in homes, community clinics, acute care hospitals, emergency departments, and skilled nursing facilities to enhance clinical care within and across settings, address the non-clinical determinants of health, and enhance healthcare utilization and costs [1]. Considering the situation of primary care in California, Coffman et al. optimized the framework for classifying the primary care workforce to enhance primary care education, improve recruitment and retention of primary care clinicians, and leverage data to inform primary care workforce strategies [8]. Deckers et al. sent out questionnaires and made field trips to show that many primary care surveillance networks exist in Europe. They also formulated some minimal criteria for primary-care-based surveillance networks [9]. Bindman et al. showed the structure of primary care in the United States and compared the system with Britain [10]. From a macro perspective, Morduchowicz et al. proposed a lean-informed approach to build an academic primary care practice of the future [11].

Simulation-based optimization can provide optimization of complex, stochastic patient flows within healthcare providers and healthcare operations management improvements with effective support. Scholars and practitioners at home and abroad have focused on the healthcare service systems governed by hospitals and have researched patient flow optimization and healthcare service operation management improvement in hospital emergency services, outpatient services, and inpatient services using discrete-event simulation-based optimization [12]. Ordu et al. designed a decision-aid system for the optimal allocation of resources such as hospital beds and medical and nursing staff based on the "prediction-simulation-optimization" framework. Framework to develop a decision-aid plan for optimal allocation of resources such as hospital beds and health care workers in hospitals [13]. Most studies have shown that optimization results obtained based on discrete-event simulation models can effectively improve the efficiency of healthcare resource utilization and significantly reduce the average waiting time for different types of patients.

This study uses a discrete-event simulation-based optimization method to study the quality and efficiency improvement of family physician contracting service operations. The difficulty of using the discrete-event simulation-based optimization method is weighing multiple primary care physician contracting service evaluation indicators. That is, how to select the optimal combination of controllable factors in the simulation experiment design based on numerous output indicators of the simulation system with stochasticity. Faced with this multi-response optimization problem, domestic and foreign researchers have explored and studied it. Considering that the simulation output indicators have some correlation with each other, the obtained statistical information reflected by the data overlaps to a certain extent; we find that the multiple response optimization based on principal component analysis is an ideal optimization tool based on discrete-event simulation [14]. Furthermore, Liao et al. innovatively investigated a multi-response optimization method based on weighted principal component analysis, which solved the negative effect of "dimensionality reduction" generated by principal component analysis [15].

A review and analysis of the existing literature suggest that scholars are actively studying the role of the primary care system on population health as a whole. However, most studies now focus on establishing primary care and evaluating the existing primary healthcare system. However, the evaluation methods mainly involve collecting data on the operation of existing systems, analyzing the data, and proposing appropriate solutions. In addition, some scholars have focused on the role of primary care in addressing specific diseases but have not considered the operation and efficiency of the primary care system. Few scholars have simulated the operation of a new primary care system after constructing it and designing evaluation indicators. Therefore, in this paper, we first design a new primary healthcare system and design multiple evaluation indicators. We also propose an improved multi-response optimization method to solve the optimization problem of various evaluation indicators in different dimensions.

3 Newly Designed Primary Care System

Our research aims to design an appropriate primary care system for our selected community. This section will introduce this community and describe the structure of direct healthcare services.

We first analyze the age and disease status of the community's residents. We divide the population of this community into six categories. There are 19,060 older people over 60 with chronic diseases, 10,580 adults between 18 and 60 with chronic diseases, and 6,780 children under seven years old with chronic illnesses in this community. In addition, the district has 802 maternal cases, 15,820 children under seven years old without chronic diseases, and 117,760 people of other ages without chronic diseases.

We made several assumptions. First, the number of births in the community equals the number of deaths. Second, the number of people leaving the community is the same as the number of people entering the community. Third, transitional care services are varied for different diseases, but in this paper, without losing generality, we fixed the frequency and length of services at three visits and one month. Fourth, primary health care services may vary for different diseases, but without loss of generality, we construct different service processes based on only six categories of people. Fifth, primary care physicians and nurses work every Monday through Friday, regardless of legal holidays.

For seniors over 60 with chronic diseases, a health assessment by a physician and nurse is required yearly. After the health assessment, 20% of the seniors need transitional care, and 80% do not. For those who need transitional care, the nurse will visit them three times within one month after the health assessment. The nurse will follow up every three months, and the doctor will follow up every six months after the transition care. For the elderly with chronic diseases who do not need transition care, only the nurse will follow up every three months, and the doctor will follow up every six months after the health assessment.

For adults between the ages of 18 and 60 with chronic diseases, a health assessment by a physician and nurse together is required every year. After the health assessment, follow-up visits are conducted every six months by the physician and every three months by the nurse.

A health assessment by a physician and nurse is required yearly, between 7 and 60 without chronic. Other than that, no follow-up is required.

For children under seven years of age with chronic diseases, the pediatric nurse will visit the child once on the first day of birth, once during the first week, once during the second week, and once during the fourth week. One month, three months, six months, and nine months after birth, the pediatrician and pediatric nurse will conduct a medical examination of the child with chronic diseases. The pediatrician and the pediatric nurse will examine children with chronic diseases at one year, 1.25 years, 1.5 years, 1.75 years, two years, 2.25 years, 2.5 years, 2.75 years, and three years. After the age of three, children with chronic diseases are followed up by a pediatric nurse every three months. The pediatrician will follow up with the chronically ill child aged four, five, six, and seven.

For children without chronic conditions, the pediatric nurse will visit the child once on the first day of life, once during the first week, once during the second week, and once during the fourth week. The pediatrician and pediatric nurse will physically examine the child without chronic disease one month, three months, six months, and nine months after birth. At the age of 1, 1.5, 2, 2.5, and 3 years for children without chronic diseases, the physician and nurse will perform a health check-up. After the child is three years old, the pediatrician will follow up with the child without chronic disease at ages 4, 5, 6, and 7.

In pregnant women's cases, the obstetrician, gynecologist, and obstetric nurse perform a separate examination in the 8th, 18th, 22nd, 30th, and 36th weeks of pregnancy. After the delivery, the obstetric nurse will make a follow-up visit to the mother in the first week and the fourth week, respectively. At 42 days after delivery, the obstetric nurse and the doctor will conduct a health check.

In addition, the community has a community hospital that requires the participation of primary care physicians. Each primary care physician must provide four hours of outpatient services twice a week at the community hospital. Each primary care physician must provide 3.5 h per week of health education on health care issues.

In this article, we focus only on three groups of people: elderly people with chronic diseases over 60 years old, adults without chronic diseases between 18 and 60 years old, and people without chronic diseases between 7 and 60 years old, and we study and optimize the primary care service process for the three groups.

4 Simulation

4.1 Simulation Structure and Parameter Settings

In designing the primary care system, we built the entire process from the first health assessment to the end of the primary care delivery process for different populations. We explored how people receive and wait for services at each step. We considered the two human resources available for primary care physicians (PCP) and nurses. Initially, we set their working hours to be 8 h per day, 5 days per week, without considering legal holidays.

Figure 1 illustrates the basic flow of the primary care system. As mentioned before, we only consider three types of people in this simulation system. We assume that patients arrive only during the eight hours from 8:00 p.m. to 4:00 p.m. each day and that the arrival rate follows an exponential distribution.

Arrival 1 represents the arrival of seniors over 60 with chronic with arrival rates of 9.16 per hour. The seniors will have their first health assessment as soon as they come. In the first health assessment, one senior needs a primary care physician and a nurse to evaluate. Primary care physicians and nurses will assess the health of older people and take up time following Triangular (30min, 35min, 45min) of doctors and time following Uniform (30min, 45min) of nurses, respectively. Then, 20% of the seniors need transition care, and 80% do not. For seniors who need transition care, service will be provided three times in the first month by a nurse who takes up the time following Triangular (70min, 75min, 80min) each time. The time includes the nurse's commuting time from the healthcare center to the patients' home and, between different patient homes. A nurse will follow up every three months after the first health assessment for each senior, with each occupancy time following Triangular (25min, 30min, 35min). A primary care physician will follow up every six months after transition care for each senior, with each occupancy time following Triangular (25min, 27min, 30min). Hence, six months after the first health assessment, a primary care physician and nurse will work together to follow up with a senior. For seniors with chronic diseases who do not need transition care, a nurse will follow up every three months after the first health assessment for

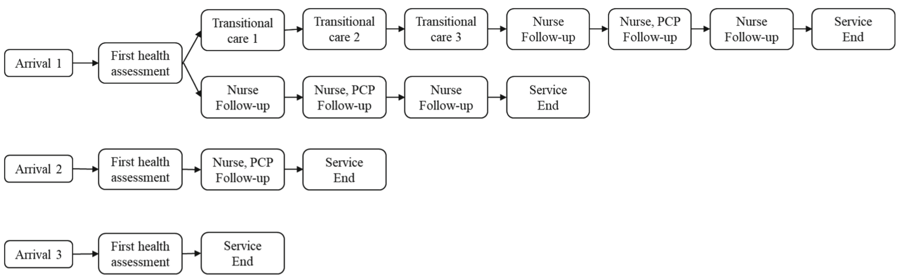

Fig. 1. Flow of primary care system in the community

each senior, with each occupancy time following Triangular (25min, 30min, 35min). A primary care physician will follow up with the nurse together after six months of the first health assessment for each senior simultaneously, with the time occupied by the primary care physician following Triangular (25min, 27min, 30min).

Arrival 2 represents arriving adults between 18 and 60 with chronic diseases with arrival rates of 5.08 per hour. The seniors will also have their first health assessment when they arrive. In the first health assessment, one adult needs a primary care physician and a nurse to evaluate. Primary care physicians and nurses will assess the health of the adults and take up time following Triangular (30min,35min,45min) of Primary care physicians and time following Uniform (30min,45min) of nurses respectively. Six months after the first health assessment, a Primary care physician and a nurse will work together to follow up with adults between 18 and 60 with chronic diseases. The processing time for each Primary care physician follows Triangular (25min, 30min, 35min), and for each nurse, the occupancy time follows Triangular (25min, 30min, 35min).

Arrival 3 represents arriving of people between 7 and 60 without chronic with an arrival rate of 22.64 per hour. They only receive the first health evaluation, which requires a primary care physician and a nurse to evaluate. Primary care physicians and nurses will assess the health of the adults together and take up time following Triangular (30min, 35min, 45min) of Primary care physicians and time following Uniform (30min, 45min) of nurses, respectively.

4.2 Simulation Experiments

We design a two-year simulation run. Initially, the system was set up with 22 primary care physicians and 56 nurses. The work week was Monday-Friday, eight hours a day. We first ran the simulation system using the available resources to explore the system operation problems. The results are shown in Table 1.

From the data in the table above, the average waiting time for those attending initial health assessment services was up to 2 months. The waiting time for those who attend follow-up services with primary care physicians and nurses is also up to 1 week, which is grossly inconsistent with the responsiveness required for service quality. At the same time, we find that nearly 40% of people could not attend the initial health assessment based on the simulation results, which is inconsistent with the reliability required for service quality.

Therefore, we need to increase the number of primary care physicians and nurses or the working hours of primary care physicians and nurses to reduce the population's

Table 1. Initial simulation based on current human resources

Service category	Average waiting time (Hour)
First health assessment	1650.8
Nurse follow-up (excluding transitional care)	5.62
Primary care physicians and nurse follow-up	158.8
Transitional care	10.8

waiting time and improve the quality of primary health care services. The three factors we chose for this experiment were the number of primary care physicians, nurses, and overtime hours. These factors can be changed in the primary care system we designed. Increasing the values of these three factors can influence the optimization of the primary health care system, as they increase the number of system resources. We choose four levels for each of these three factors. We determine the values at different levels for each factor by changing the number of resources of one kind at a time in the simulation system and running it. When the number of primary care physicians is around 40, the average waiting time of the population for all services is significantly reduced. Therefore, we increase the number of human resources of primary care physicians evenly at each level. Also, when the number of nurses is around 70, the average waiting time of the population in all services decreases somewhat. Therefore, we increase the number of human resources of nurses evenly at each level. We assume a maximum working time of 11 h per day, which means up to three hours of overtime per day The number of human resources for each factor and their ranking are shown in Table 2.

After designing the factors and their levels, we apply the Taguchi method to design an L_{16} experiment as shown in Table 3. For example, in Exp. No 2, the combination of factors and levels that we choose to run in the simulation system is $A_1B_2C_2$, which means the first level of the number of primary care physicians, the second level of the number of Nurses, and the second level number of overtime. For each level, we choose the middle number of this level as the parameter of this level for simulation experiments. We design 16 experiments, and for each experiment, we perform three simulations to balance the effects of chance errors.

For each experiment, we design three responses, salaries of primary care physicians and nurses, the average waiting time of the population, and the percentage of the population not receiving services. The average waiting time of people, which represents the responsiveness of services. We calculate the average waiting time for the people involved in each service process. The salaries for primary care physicians and nurses represent the cost of the service quality. We assume that the hourly rate for a general practitioner is ¥72 and for a nurse is ¥48, with double pay for overtime. The percentage of the population not receiving services reflects the reliability of the service, and we obtain an average for the number of non-participants at each service step.

After obtaining each response's value, we apply the WPCA method to analyze. The WPCA method is a method that first preprocesses different categories of sample data,

Table 2. Factors and their levels

Levels	Number of Primary care physicians (A)	Number of Nurses (B)	Overtime (C)
1	22 – 26	56 – 60	0
2	27 – 31	61 – 65	1 h
3	32 – 36	66 – 70	2 h
4	37 – 41	71 – 75	3 h

Table 3. Combination of levels and factors in L_{16} experiment

Exp. No		L_{16}	
	Waiting Time (A)	Salaries (B)	Ratio of non-participating(C)
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1
12	3	4	2
13	4	1	4
14	4	2	3
15	4	3	2
16	4	4	1

then calculates weights using the feature relationships between different categories in the data, weights the data samples, and later performs feature extraction using PCA [16, 17, 18]. In this article, we apply the WPCA approach to the data of the three response variables.

We first compute each response's quality loss and SN ratios to solve multiple-response problems. Then, we normalize the SN ratios of each response and transform their normalized response performance into a muti-response index by PCA. There are three principal components, and the relations between principal components and responses are.

$$\begin{aligned} Z_1 = & -0.7346 \times Average\ waiting\ time\ of\ population \\ & -0.1191 \times Salaries\ of\ Primary\ care\ physicians \\ & +0.6680 \times Percentage\ of\ population\ not\ receiving\ service \end{aligned} \tag{1}$$

$$\begin{aligned} Z_2 = & 0.2203 \times Average\ waiting\ time\ of\ population \\ & +0.8893 \times Salaries\ of\ Primary\ care\ physicians \\ & +0.4007 \times Percentage\ of\ population\ not\ receiving\ service \end{aligned} \tag{2}$$

$$Z_3 = 0.6418 \times Average\ waiting\ time\ of\ population$$

$$- 0.4415 \times Salaries\ of\ Primary\ care\ physicians$$
$$+ 0.6270 \times Percentage\ of\ population\ not\ receiving\ service \quad (3)$$

We combine Z_1, Z_2, andZ_3 to get MPI value. The formula for calculating the MPI values is shown below, and the results are presented in Table 4.

$$MPI = 0.0185 \times Z_1 + 0.1316 \times Z_2 + 0.8499 \times Z_3 \quad (4)$$

Finally, we will calculate the main effect of each factor's level, as shown in Table 5. The best combination of factors and levels is $A_4B_2C_4$, which means the fourth level of the number of primary care physicians, the second level of the number of nurses, and the fourth level number of overtime.

Table 4. Data summary of the MPI

Exp. No		L_{16}		MPI
	Waiting Time (A)	Salaries (B)	Ratio of non-participating(C)	
1	1	1	1	-0.2605
2	1	2	2	-0.1144
3	1	3	3	0.0320
4	1	4	4	0.1692
5	2	1	2	0.0023
6	2	2	1	-0.0988
7	2	3	4	0.4909
8	2	4	3	0.2294
9	3	1	3	0.6101
10	3	2	4	1.0351
11	3	3	1	0.0506
12	3	4	2	0.3226
13	4	1	4	1.1589
14	4	2	3	1.1180
15	4	3	2	0.9370
16	4	4	1	0.3515

Table 5. Main effects table

Factors	**1**	**2**	**3**	**4**
A	-0.04342	0.155939	0.504604	0.891344
B	0.377718	0.484969	0.37761	0.268167
C	0.010707	0.28687	0.497375	0.713513

5 Conclusion

We designed a new primary healthcare system and determined the number of primary care physicians to be 37–41, the number of nurses to be 61–65, and overtime to be 3 h by using discrete-event simulation and multi-response variable analysis. However, the system has many limitations. The current primary care system could be optimized, for example, by adding Internet hospitals at a later stage to reduce home visit times. The current number of factors and responses is small and does not measure the whole system from a finer perspective. Subsequent studies will increase the number of factors and responses to evaluate the system better.

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