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System Dynamics Modeling for Contactless Delivery Strategy of Medical Supplies

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Abstract. The contactless delivery of drugs under the novel coronavirus pneumonia epidemic has become one of the main research trends. In this paper, an optimization model of contactless distribution of drugs under the epidemic is constructed based on the system dynamics simulation, considering the medical prescriptions of spare drugs in the cabin and the workflow of contactless drug distribution by unmanned vehicles. Finally, the model and algorithm are validated by taking the drug delivery of Wuhan city mobile cabin hospital under the new coronavirus pneumonia epidemic as an example. By adjusting the parameters and continuously simulating and optimizing, we study the use of contactless technology in drug distribution in mobile cabin hospital, clarify the practical value of the technology, and analyze the distribution efficiency, distribution cost and inventory changes before and after its use. The results show that the model constructed in this paper takes into account the time delay caused by quarantine and disinfection in distribution, which can more realistically reflect the distribution scenarios and influencing factors in the hospital environment, reasonably plan the unmanned vehicle scheduling work, and maximize the benefits of the contactless drug distribution system.

Keywords. System Dynamics; Contactless Delivery; Medical Supplies; Drug Distribution.

1. Introduction

Since the new WHO International Health Regulations added "public health emergencies of international concern", the supply of medical protective materials and medicines has gradually come under the spotlight. It is reported that in the early stage of covid-19 epidemic in China, 1716 cases of medical staff were reported, accounting for 3.8% of the country; Hubei Province reported 1502 confirmed cases of medical staff, accounting for 87.5% of the confirmed cases of medical staff in China [1]. Therefore, under the COVID-19 epidemic, it has become an urgent problem to optimize the drug dispensing mode and minimize the infection rate of medical personnel by ensuring timely supply of drugs.

Although COVID-19 epidemic has promoted the continuous development of contactless distribution technology, but contactless distribution has been associated with higher technical costs, and there is a lack of a relatively quantitative evaluation scheme

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to determine the distribution costs and distribution efficiency of contactless technology. There are many factors affecting the contactless distribution of medical supplies. On the one hand, the characteristics of the unmanned vehicles themselves, such as different delivery modes of unmanned vehicles and different loads and power of different types of unmanned vehicles. On the other hand, logistics factors, such as drug demand, delay time, distribution cycle and inventory status. In short, the simulation of contactless distribution of medical supplies includes nonlinear dynamic feedback of multiple business processes in multiple situations [2]. The system dynamics simulation method is suitable for dealing with this kind of periodic high-order nonlinear dynamic complex systems. The problem of insufficient data in modeling can be solved by calculating and analyzing the causal relationship in the model.

Therefore, based on the system dynamics approach, this thesis investigates the unmanned distribution demand, distribution cost and efficiency of drugs in the mobile cabin hospitals designated for treatment during an epidemic outbreak, and continuously optimizes the simulation to seek the optimal dispatching scheme for the contactless technology. As far as possible, we provide theoretical and data support for the process of unmanned vehicle distribution of drugs in mobile cabin hospitals, and provide a suitable cost budget for the contactless distribution of drugs. It provides meaningful references for improving the safety of material distribution, reducing interpersonal contact, improving distribution capacity, promoting contactless distribution mode, and strengthening epidemic prevention and control.

1. Literature Review

1.1. Distribution of medical supplies under epidemic situation

From the perspective of medical supplies distribution outside the hospital, the rapid spread of the epidemic, the lack of raw materials and manpower reserves, the limited capacity of supplies, and the inefficiency of emergency supplies dispatch, it is not easy to consider the degree of priority of medical supplies and the uncertain dispatch of multi-point distribution under the conditions of insufficient supplies during the epidemic outbreak [1-3]. More importantly, medical supplies distribution during the epidemic increased the risk of infection among medical staff and reduced the labor force [4]. In general, the current medical supply distribution challenges under the epidemic mainly rely on contactless distribution technology to accomplish.

1.2. Contactless delivery of medical supplies

With the outbreak of covid-19 epidemic, the demand for contactless distribution of medical supplies in hospitals is increasing rapidly. Among them, uttam U. Deshpande et al. have developed an unmanned guided car for drug distribution, which has low cost and no track [5]. Chen, Shunda et al. to explore new drug dispensing pattern in mobile cabin hospitals under coronavirus disease 2019 (COVID-19) circumstances, the contactless drug delivery was carried out by using 5G cloud technology and unmanned vehicle [1]. Huilin Li et. al. designed an intelligent express box for contactless distribution of medical supplies, and optimized the distribution path based on the implementation points of sharing economy and open-loop distribution to achieve the goal of low-cost and low-carbon economy [6]. Debapriya Banik et al. proposed a contactless distribution scheme of UAV medical supplies applied to urban areas and remote rural areas [7].

In summary, scholars' research focuses on how to more effectively use unmanned vehicles, the Internet of Things, and artificial intelligence technologies, and focuses on contactless delivery of medical supplies from the perspectives of innovation of contactless technology, algorithm optimization of delivery paths, and location of delivery points [8,9].

1.3. Distribution and System Dynamics

In the face of complex dynamic systems, system dynamics is used to study the flow and stock, causality in the model through quantitative and qualitative methods, so that it can accurately simulate the model in reality and provide researchers with data for support and decision making [10-12]. System dynamics is widely used in the field of logistics, such as warehousing, distribution simulation and path optimization [13-14]. Distribution, as an important part of the supply chain, is usually integrated into the analysis of the supply chain during modeling and simulation.Many literature focuses on distribution route selection, distribution node design, and distribution costs in supply chains using system dynamics, and the objects are mainly urban logistics, commodity supply chains, or disaster relief and emergency logistics [15-17].

Although they have analyzed the optimization of distribution routes and the location layout of distribution points in the supply chain using system dynamics methods, it is worth mentioning that there are still few studies on the cost, cycle time, and benefits of contactless distribution of medical supplies within hospital premises [18-20]. To sum up, the design of a model for contactless distribution of medical supplies under an epidemic is an important research problem.

2. Methodology

System dynamics can observe the behavior trend and change trend of the system at different times by dynamically setting the control factors [21-22]. Therefore, this paper uses the system dynamics method to analyze the application of contactless distribution technology in fixed-point treatment hospitals, and further discusses the demand for contactless distribution of medical materials during the epidemic.

2.1. Background Analysis

The real distribution process and data of mobile cabin hospital in Wuhan Guanggu Science and Technology Exhibition Center are selected as the empirical background. The mobile cabin hospital of Guanggu Science and Technology Exhibition Center is an intelligent mobile cabin hospital with 5G cloud technology. It has a total area of about 10,000 square meters and can accommodate 850 beds. There are three wards of A1, A2 and A3, including four supporting service areas: entrance and exit, buffer zone, washing area and treatment room. It is mainly used for the treatment of mild patients with new coronavirus pneumonia infection. The hospital adopts the BXN-01 unmanned vehicle (Beijing White Rhino Cattle Zhida Technology Co., Ltd., size: 2.5m * 1.0m * 1.8m, loading capacity 2.15m^3, endurance 100km, maximum speed 45km / h) to carry out drug dispensing and drug contactless distribution [1].

Since it is a designated hospital specializing in the treatment of New Coronary Pneumonia, which involves sterilization and quarantine, its drug dispensing and distribution model has special characteristics in order to reduce cross-infection. Before using the unmanned delivery technology, the process is as follows: First of all, the cabin doctor prescribes the medication medical advice before the end of the shift, and the pharmacist reviews the medical advice and then allocates the medication, next, the special person delivers it to the cleaning room of the mobile cabin hospital, and then, the receiving medical staff enters the cabin and brings it to the treatment room, and then distributes the medication. The process of using unmanned vehicles for in cabin drug distribution is as follows: First, the drugs enter the hospital from outside the hospital and are stored in the staging area, the physician reviews the medical prescription through the system, prints the medical prescription dispensing order, and dispenses the prescription, and after dispensing, the drugs are taken and packed according to the cabin partition, loaded into the unmanned vehicle, and sent to the backstage technician. The backstage operates the unmanned car through 5G technology to enter the cabin from the patient channel and arrive at the treatment room. The nurse inside the cabin scans the code and opens the box, distributes the medicine according to the medical prescription, and sends out the cabin command after completion. The backstage receives the instruction and turns on the car's built-in UV disinfection lamp to disinfect. The unmanned vehicle arrives at the buffer zone after leaving the cabin, disinfects for 1 hour, and is ready for use after disinfection [1].The highly automated drug distribution system can reduce human labor, reduce the demand for protective materials and improve the distribution efficiency. In particular, the risk of doctor-patient cross infection is greatly reduced.

2.2. System Boundary

This paper will establish a model around the drug distribution system within the hospital. Therefore, the definition of the model should be set around the loading link, the entry link, the killing link and the exit link of the drugs in the cabin. The boundary diagram of model is shown in Figure 1. The solid line frame represents the boundary of the system, in which the hospital drug delivery process covers the drug packaging vehicle area, treatment room and buffer zone of the hospital.

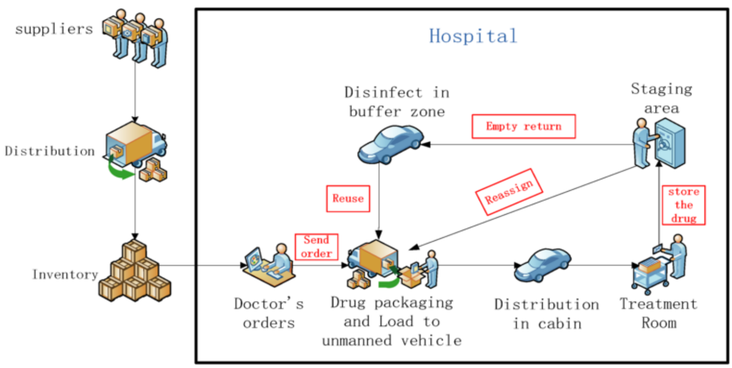


Figure 1. Boundary of delivery system diagram

2.3. Assumptions of the Simulation Model

The following assumptions are put forward when establishing the model:

• There are three modes of medical prescription within the hospital: long-term medical prescription, temporary medical prescription and in-cabin standby. The medication demand and drug distribution process of different medical prescription modes vary greatly, and the model only considers the distribution demand of in-cabin standby which is small in size, large in quantity and relatively single and repetitive in distribution.

• Extreme conditions in the distribution system are not considered during the study time period, i.e., unmanned vehicle equipment, medical personnel, etc., all proceed normally as planned.

• Patient demand during the study period was within a certain range and did not show extremes.

• The supply of drugs is sufficient and there is no shortage of stock.

• Assuming a treatment room safety stock of 100.

• Unmanned vehicles deliver drugs with a single fixed point of delivery, and there is no coordinated delivery.

2.4. Causal Loop Diagram

The causal loop diagram shows the causal behavior from the perspective of the system, which is helpful to intuitively understand the relationship between different variables in the system. According to the previous introduction of the in-hospital distribution system and the actual situation of the distribution process, as well as the parameters involved in the model, the Vensim Ple software was used to construct the causal loop diagram of the in-hospital distribution system of the mobile cabin hospital (The main variables in the model and their acronyms are shown in Table 1). These variables are connected by a causal chain representing positive feedback (plus sign) and negative feedback (minus sign) [23].

Table 1. Variables in the model

Number	Variable	Acronym
1	Doctors' orders	DO
2	The productivity of doctors' orders	PDO
3	Stock adjustment rate of doctors' orders	SARDO
4	Stock adjustment time of doctors' orders	SATDO
5	Stock of doctors' orders	SDO
6	A Time delay of redistribution for doctors' orders	TDRDO
7	Redistribution for doctors' orders	RDO
8	The proportion of redistribution for doctors' orders	PRDO
9	Opening inventory of drug packing area	PIDPA
10	Delivery rate of doctors' orders	DRDO
11	Delivery time of doctors' orders	DTDO
12	Delivery of doctors' orders	DDO

Table 1. *(continued)*

Number	Variable	Acronym
13	Inventory of drug packing area	IDPA
14	Stock adjustment rate of drug packing area	SARDPA
15	Stock adjustment time of drug packing area	SATDPA
16	Safety stock of drug packing area	SSDPA
17	Delivery time of drug packing area	DTDPA
18	Delivery rate of drug packing area	DRDPA
19	Opening inventory of drug in treatment room	OIDPA
20	Inventory of drug in treatment room	IDTR
21	Stock adjustment time of drug in treatment room	SATDTR
22	Stock adjustment rate of drug in treatment room	SARDTR
23	Safety stock of drug in treatment room	SSDTR
24	Delivery time of treatment room	DTTR
25	Delivery rate of treatment room	DRTR
26	Inventory of temporary storage area	ITSA
27	Opening inventory of temporary storage area	OITSA
28	Order rate of drug in temporary storage area	ORDTSA
29	Stock adjustment time of drug in temporary storage area	SATDTSA
30	Stock adjustment rate of drug in temporary storage area	SARDTSA
31	Safety stock of drug in temporary storage area	SSDTSA
32	Delivery time of drug in temporary storage area	DTDTSA
33	Opening inventory of external using	OIEU
34	External utilization rate	EUR
35	Potential needs of patients	PNP
36	Number of unmanned vehicles	NUV
37	Single cost of unmanned vehicle	SCUV
38	The change rate of distribution cost	CRDC
39	Distribution cost	DC
40	Inventory of utilization drug in temporary storage area	TUDTSA
41	Ratio of utilization drug in temporary storage area	RUDTSA
42	Utilization of utilization drug in temporary storage area	UUDTSA
43	Time delay of utilization drug in temporary storage area	TDUDTSA
44	The proportion of drug in temporary storage area	PDTSA
45	Time delay of drug in temporary storage area	TDDTSA
46	Stock adjustment time of drug in temporary storage area	SATDTSA
47	Order rate of drug in treatment room	ORDTR
48	Repackaging rate	RR

2.5. Simulation Model Formulation

2.5.1. Flow Stock Diagram

The flow stock diagram is a graphical representation that further distinguishes the nature of variables on the basis of the causal loop diagram, describes the logical relationships between system elements with more intuitive symbols, and clarifies the feedback forms and control laws of the system [24]. Through the analysis of each influencing factor of the drug distribution system within the mobile cabin hospital, the flow stock diagram of the contactless drug distribution system was drawn, as shown in Figure 2.

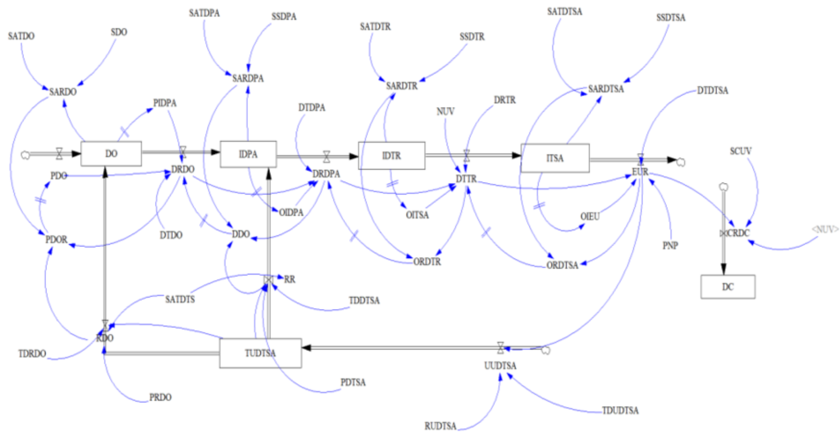


Figure 2. Flow stock diagram based on contactless drug distribution system

2.5.2. Mathematical Formulation

In this paper, combined with the actual data of the corresponding case, the mathematical equations of the variables are established. Among them, since the level variables and the rate variables are the key types of variables studied in the logistics distribution model, they are presented separately in a list, as shown in Table 2.

Table 2. The stock of equation

Number	The Stock of Equation	Unit
1	DO=INTEG((DELAY1I(PDO, 1 , 0) - DRDO + RDO,0)	Piece
2	IDPA=INTEG((DELAY1I(DRDO,1 ,0) - DRDPA + RR),0)	Piece
3	ITSA=INTEG(DELAY1I(DRDPA,1 , 0) - DTTR,0)	Piece
4	ITSA=INTEG(DELAY1I(DTTR, 1 , 0) - EUR,0)	Piece
5	TUDTSA=INTEG(UUDTSA - RR - RDO,100)	Piece
6	DC=INTEG(CRDC,0)	RMB

Meanwhile, the main rate variable equations in this paper are as follows:

DRDO=MIN(PIDPA/DTDO+PDO, DELAY1I(DDO, 5, 0)) (1)

DRDPA=MIN(OIDPA/DTDPA+DRDO, DELAY1I(DTTR, 5, 0)) (2)

EUR=MIN(OIEU/DTDTSA+DTTR, SMOOTH(PNP, 2)) (3)

RDO=DELAY1(TUDTSA*PRDO/SATDTSA, TDRDO) (4)

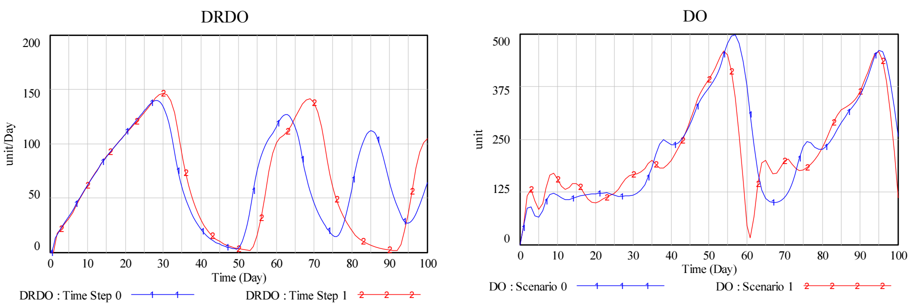
There are also some auxiliary variables as well as constants in the model, whose equations and coefficients are shown in Table 3.

Table 3. Auxiliary variables and parametric equations

Number	Auxiliary Variables and Parametric Equations	Type of variable
1	PIDPA=DELAY1I(DO, 1 , 0)	Auxiliary variable
2	SARDPA=(SSDPA - IDPA)/SATDPA	Auxiliary variable
3	ORDTR=DELAY1I(DTTR, 1 ,0) + SARDTR	Auxiliary variable
4	SADTO=3	constant
5	SSDPA=120	constant
6	PNP=1200*RANDOM NORMAL(1, 2 , 1.5 , 2 , 99)	constant
7	DTDO=2	constant
8	TDDTSA=1	constant
9	DTDTSA=2	constant
10	TDUDTSA=2	constant
11	RUDTSA=0.3	constant
12	DTDPA=2	constant
13	SATDTSA=2	constant
14	TDRDO=1	constant

2.6. Model Validation

System dynamics is the science of studying the behavior of systems and their structures. The rationality of system dynamics modeling requires testing of the model. only the following test items are usually completed: system boundary test; step size test; model structure and its behavior test; parameter estimation test; integration error test; consistency of magnitudes test; extreme scenario test; and sensitivity test [25].



(a) (b)

Figure 3. Test chart

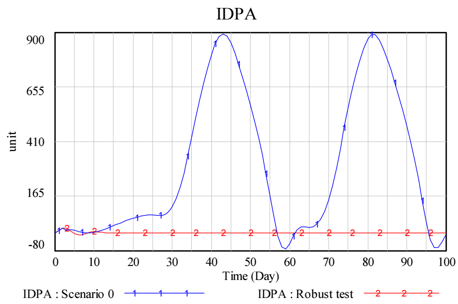


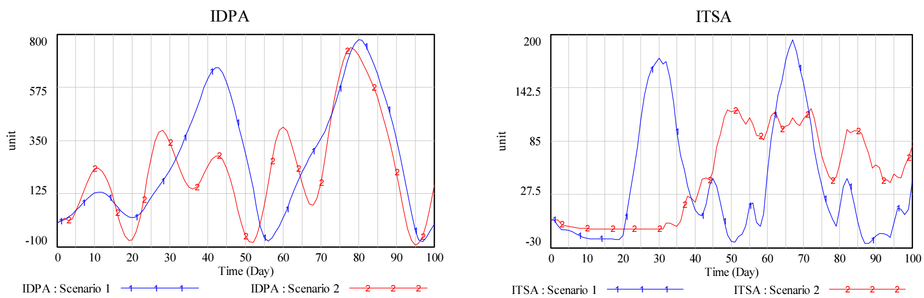
Figure 4. Test chart

In this paper, according to the actual situation, the above system boundary test, step size test, sensitivity test, extreme scenario test, and consistency test are selected to test and analyze the model, and finally pass the test to prove that the model can be used for subsequent simulation. All tests passed, the test results are shown in the Figure 3 and Figure 4.

3. Analysis of Experimental Results

3.1. Analysis of Key Influencing Factors of Distribution System

Tn order to study how to study the distribution efficiency and distribution cost influencing factors of the drug distribution system before and after the contactless distribution technology in a more cost-efficient way, the bullwhip effect of contactless distribution and the distribution cost are related to the analysis and focus on finding the key influencing factors.



(a) (b)

Figure 5. Distribution cost simulation

As shown in Figure 5(a) After reducing the adjustment cycle of drug transportation, it can be found that the oscillation of zoned packing inventory in the unmanned vehicle compartment is significantly reduced, which in turn significantly reduces the inventory cost in the distribution process, and thus improves the distribution and transportation efficiency. Therefore, reducing the adjustment cycle of drug transportation and improving the response speed in the distribution process can appropriately reduce the cost of distribution and improve the efficiency of distribution.

As shown inFigure 5(b) After reducing the adjustment period of drug transportation, it can be found that the stock shock of drugs in the staging area is significantly reduced. As the end node of distribution and handover in the shelter hospital, the temporary storage area can reduce the inventory shock, effectively reduce the distribution pressure, improve the distribution and transportation efficiency, reduce the backlog of drugs in stock in the distribution process, and improve the turnover and delivery rate of drugs.

After the adjustment cycle for drug transportation was reduced, the number of deliveries that needed to be made for later transportation was significantly reduced due to the significant reduction in the wave of materials that needed to be stored in the inventory of each segment, which in turn improved the efficiency of distribution and reduced the cost of later distribution. The model simulation data reveals that the distribution cost is reduced by about 28.6% after the adjustment cycle reduction is performed. As shown in Figure 6 .

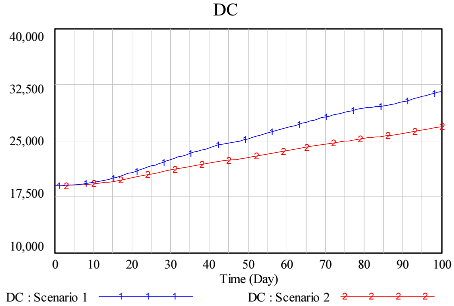
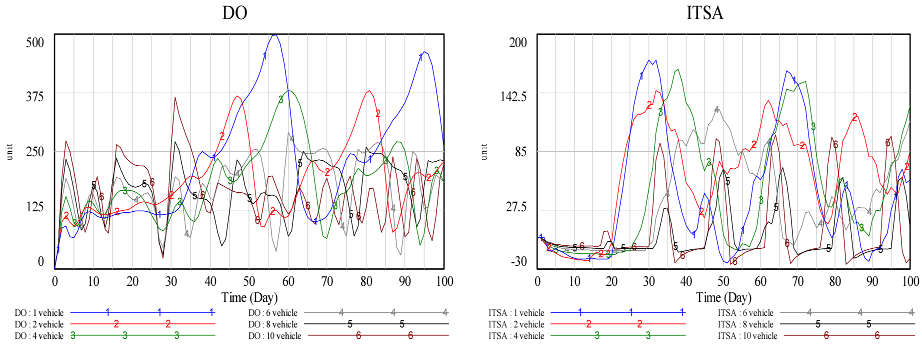


Figure 6. Distribution cost simulation

3.2. Requirement Analysis of Unmanned Vehicle Configuration

In order to objectively evaluate the demand for the number of unmanned vehicles in the mobile cabin hospital of the model from more angles, and quantify the research indicators, the number of unmanned vehicles simulation is carried out for the model. Considering the small area of the mobile cabin hospital, the demand for unmanned vehicles is only limited to the distribution of the medical prescriptions of spare drugs in the cabin, so six simulation scenarios are set, increasing from one vehicle to the next, including one vehicle, two vehicles, four vehicles, six vehicles, eight vehicles and ten vehicles. The simulation results are shown in Figure 7. The simulation results show that with the increase of the number of unmanned vehicles, the doctors'orders and inventory of temporary storage area show similar fluctuations. When the number of vehicles increases to 8, the fluctuation range becomes smaller, and the simulation fluctuations of 8 vehicles and 10 vehicles tend to be the same. This shows that when more than 8 vehicles are configured, the demand fluctuation of standby drug dispensing and the inventory fluctuation in the distribution system are the smallest, the distribution demand tends to be stable, the in transit inventory is reduced, the stable supply of drugs is ensured, and the backlog of drugs in stock is reduced. Therefore, it is the most economical for the mobile cabin hospital in Wuhan Guangdong science and Technology Exhibition Center in this model to be equipped with 8 unmanned vehicles. Of course, the model is also applicable to the number of unmanned vehicles in other hospitals.



(a) (b)

Figure 7. Vehicle simulation

3.3. Distribution Cost Analysis

In terms of cost, the cost of an unmanned vehicle needs 100,000 yuan, safe and reliable, low post-care costs, according to the design life of 5 years to record. Then the fixed cost of a single unmanned vehicle is as follows.

The residual value of the unmanned vehicle at the fifth year is:

$$100000\times5\%=5000\ RMB \tag{5}$$

The annual depreciation charges are:

$$(100000\text{-}100000\times5\%)/5=19000\ RMB \tag{6}$$

The annual depreciation expense is regarded as the fixed cost of the unmanned vehicle, while the equipment maintenance expense, management expense and other daily operating costs of the unmanned vehicle are included in the variable cost of the unmanned vehicle. According to the statistics of the unmanned Distribution Department of meituan company, the average distribution cost of unmanned aerial vehicles when delivering takeout is 7-8 RMB per order. Therefore, it is considered to set the daily operation cost of short-distance unmanned vehicles in the hospital as 1 yuan per order. By simulating the distribution cost of a single unmanned vehicle in the benchmark scenario and the optimization scenario, the simulation data of the distribution cost is obtained.

It can be seen from Table 4 that during 90 days of simulation, the cumulative cost of a single unmanned vehicle under the benchmark scenario is 30191 yuan, and the simulation result of the optimized model is 25961 yuan. The model simulation data show that the cumulative use cost of a single unmanned vehicle during the three months under the epidemic is about 25961-30191 yuan. The treatment cost of covid-19 mild patients is 17000 yuan, and the treatment cost of severe patients is higher, even up to 200000 yuan. According to the website of the State Commission for Discipline Inspection of the Central Commission for Discipline Inspection of China. According to the official wechat of the people's Bank of China, from January 22 to February 23, 2020, the national treasury at all levels allocated 61372 funds for epidemic prevention and control, with an amount of 8.93 billion yuan. This data does not include a large number of private material donations. In such a large economic consumption, the unmanned vehicle distribution mode can not only reduce the infection risk of medical personnel, but also save the consumption of human resources and protective materials.

Table 4. Distribution cost of single unmanned vehicle

Time (Day)	30	60	90
Scenario 1：Distribution cost	22487RMB	26747RMB	30191RMB
Scenario 2：Distribution cost	21066RMB	23669RMB	25961RMB

4. Conclusion

The sudden increase in demand for in-hospital drug delivery in sentinel hospitals during the epidemic, coupled with the risk of cross-infection between doctors and patients, has increased the complexity of the drug delivery process within mobile cabin hospitals, and thus highlighted the advantages of contactless delivery technology applied to hospital drug delivery. Therefore, hospitals should explore the benefits of deploying unmanned vehicles and quantify the value of contactless drug delivery. This study explores the delivery costs and configuration requirements of unmanned vehicle technology within a mobile cabin hospital in the context of a real-world case, taking into account not only the characteristics of the hospital's medical orders, but also the delays generated by the need for epidemic prevention in the delivery chain, and the contactless distribution behavior of drugs in the mobile cabin hospital is analyzed by constructing the system dynamics model. In order to achieve this goal, the actual situation of the mobile cabin hospital was first studied and the modules and logic of the system were specified. Then, the necessary data were collected and analyzed for the developed model, which was used to specify the mathematical functions of the variables in the model. Through continuous simulation and optimization, key influencing factors such as the adjustment period of drug transportation and the bullwhip effect of the distribution system were identified, and the configuration requirements of unmanned vehicles and the cost of single vehicle distribution of unmanned vehicles in the mobile cabin hospital under the background of the case are analyzed.

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