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An NSGA-II-based for Configuration Optimization of Shuttle-carrier Warehousing System

Wei Yang, Wei Ma, Ting Wang, and Ting Yue

School of Mechanical and Electrical Engineering, Shaanxi University of Science and Technology, Xi'an 710021, China

Abstract

This paper studied the configuration optimization problem of the shuttle-carrier warehousing system (SCWS), and proposed a multi-objective optimization solution to achieve maximizing system throughput while minimizing total cost and energy consumption. According to the storage system configuration planning principle and the benefit-reverse relationship, we considered the nine decision variables including the three-dimensional of the storage racks and the physical parameters of the equipment, and established a multi-objective optimization model for the SCWS with the shortest average throughput time, the lowest energy consumption and the lowest total cost. We used the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) with Elite Strategy to solve the model and obtained the Pareto frontier. Each the Pareto optimal solution can be used as the optimal configuration for shuttle-carrier warehousing system. This paper can provide an reliable reference for warehouse designers, according to the characteristics of the company's stored goods,they may select the appropriate shelf size to suit different needs, and the area of the leased warehouse can be determined.

Keywords

Shuttle-carrier Warehousing System; Configuration Optimization; Optimization Model.

1. Introduction

The Shuttle-Carrier Warehousing System (SCWS) is a new type of automated warehousing systems, which is mainly applied to stock keeping units (SKUs) with high usage frequency. Compared with the traditional Automated Storage and Retrieval Systems(AS/RS), the SCWS has great advantages in terms of shelf investment cost, space utilization and cargo storage efficiency. In the SCWS, the elevator and the shuttle move independently and work together. It greatly increases the storage capacity, and makes more reasonable use of the storage space, because the traditional shelf-type shelves are changed to track-type multiple-deep storage lanes [1].

It is usually important to set the system configuration based on demand. Research on the configuration problem of the SCWS, it can reduce waste in the early stage of construction and reduce the logistics cost of enterprises. This requires us to comprehensively consider the goals of efficiency, cost, and energy consumption. Although these goals are interconnected, they are also mutually exclusive. Following the anti-benefit relationship, that is, while one element in the system is optimized and benefits are generated, there must be another or the loss of several other factors' benefits.

Based on the above considerations, the configuration optimization of the SCWS is mainly divided into three steps: firstly, analyze the factors that affect system throughput time, energy consumption, and storage cost according to the operation process of the storage system; then establish a multi-objective optimization model with the shortest storage system throughput time, minimum energy consumption, and minimum storage cost as optimization goals; finally, the multi-objective optimization algorithm is used to solve the model, obtain the optimal storage system configuration plan, which provides theoretical guidance for decision-making in the early planning of the storage configuration of the enterprise.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature. Section 3 is the system description. Section 4 establishes configuration optimization model of the SCWS. Section 5 includes a numerical experiments and optimization results. Section 6 conducts analyses and evaluation of simulation results, and finally Section 7 draws the conclusion and provides some insights for the future work.

2. Literature Review

At present, there are few literatures on the related aspects of configuration of SCWS. Many researches are mainly focused on AS/RS and Shuttle-Based Storage and Retrieval System (SBS/RS). The research ideas and results of these studies still have certain reference value for studying SCWS.

For AS/RS, Jingjing Hao et al. [2] and Xianhao Xu et al. [3] studied the optimal design of AS/RS with the I/O port at the lower mid-point of the storage rack. Jingjing Hao optimized the three dimensions of the storage rack by calculating the expected travel time under the single command cycle. Xianhao Xu et al. established the travel time model under the dual command cycle, and verified the analysis models using simulation, and obtained the best ratio of storage rack height, length and depth. Xiaolong Guo et al. [4] established a travel time model based on space consumption, and compared the performance of random, full turnover-based and class-based storage policies for a unit-loads warehouse in single-command mode. The results showed that the optimal storage rack shape factor (ratio of warehouse width to depth) decreases with the skewness of the demand curve.

For SBS/RS, Zhao Ning et al. [5] developed an efficient simulation model for rack configurations of SBS/RS, and obtained the optimal rack design by simulating 81 different rack alternatives. Banu Yetkin Ekren et al. [6,7] performed the best rack design for SBS/RS under class-based storage policy (CSP).They considered rack design concepts include number of aisles, bays, and tiers. The simulation of 294 experiments were carried out. The performance of system was evaluated according to average utilization of lifts and cycle times of storage/retrieval goods. The results showed that performance is better under high rise warehouse design. WANG Yanyan et al. [8] established a two-stage open queuing network model for the multi-layer shuttle storage system and analyzed the interactions among outbound task time, shuttle waiting period, and lift idle period. The effects of different numbers of shuttles on system efficiency were analyzed.

In order to optimize the configuration of the automated storage system, the researchers in the above literature considered the three-dimensional size of the storage rack, that is, the number of tiers, the number of rows and the number of columns impact on system performance (Jingjing Hao et al [2], Xianhao Xu et al [3], Guo [4], Zhao Ning et al [5], Banu Yetkin Ekren et al [6,7]) or impact of devices quantity on system scheduling time (WANG Yanyan[8]) when planning the warehouse. It can be seen that, there are two limitations in these researches of the predecessors for the configuration optimization of automated storage system: Firstly, many scholars only unilaterally require the higher the throughput performance of the system, but the enterprise should consider the system throughput performance, as well as the initial investment cost and the system energy consumption during the operation in the initial stage of investment planning. Secondly, most scholars study the influence factors of system performance are relatively single, which leads to certain limitations of the scope of application of simulation results, and the efficiency of warehouse operation in the actual application process is affected by many factors.

Therefore, this paper comprehensively considered the impact of storage rack size and equipment movement parameter setting on the design of the SCWS, and reduced the enterprise investment cost and system operation energy consumption while ensuring that the system throughput performance meets the enterprise requirements.

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In the study of SCWS, this paper analyzed the system configuration planning principle and the benefit-reverse relationship, considered the influence of 9 decision variables (three-dimensional design of rack, equipment motion parameters), and established a multi-objective optimization model with the shortest average throughput time of system, the lowest energy consumption and the lowest initial cost of investment. On this basis, the paper used NSGA-II algorithm to solve the model and analyze the results. The results of the study can be used to guide the design and configuration optimization of the SCWS.

3. System Description

3.1 Problem Description and Related Assumptions

The configuration optimization of the SCWS is mainly to carry out reasonable resource allocation under the condition of meeting the requirements of the enterprise for throughput capacity, so as to maximize the system throughput and minimize the cost and energy consumption. During the operation of the SCWS, the movements of the unit loads at horizontal plane is achieved by the shuttle-carrier, in which the shuttle realizes the transports on the shuttle main track (x-direction movement), the carrier carries out the movements of the unit loads within the storage lanes (z-direction movement). And the lift completes the movements of the unit loads in the vertical direction(y-direction movement). The structure sketch map of Shuttle-Carrier Warehousing System is shown in Figure 1.

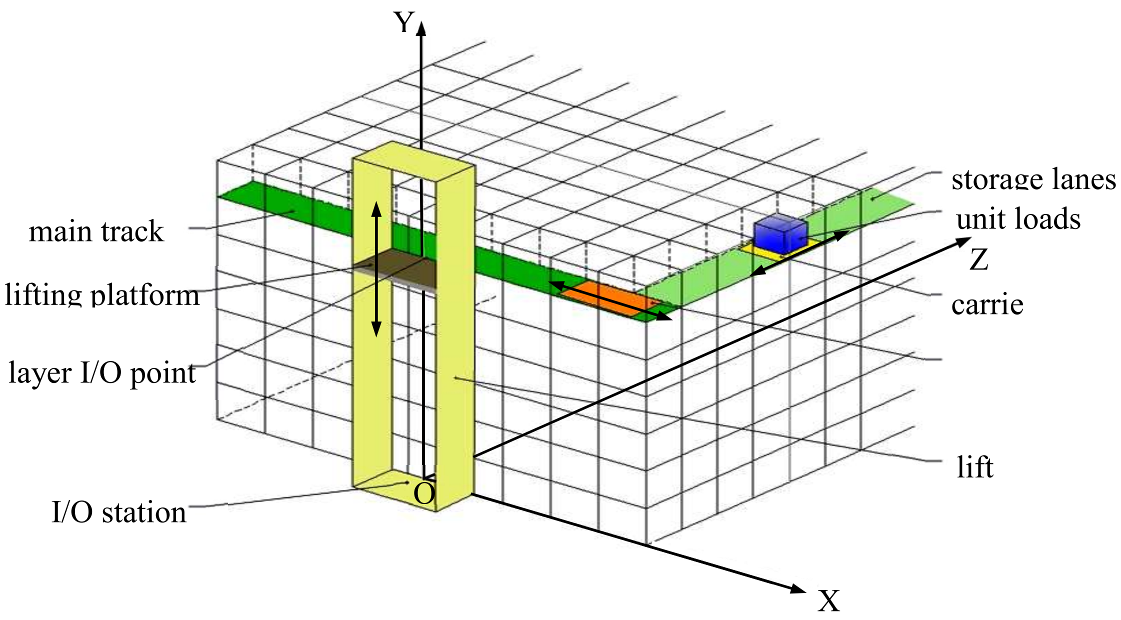


Figure 1. Structure sketch map of shuttle-carrier warehousing system

The travel cycle is the smallest unit of the operation of the SCWS. There are usually two different travel cycle modes during the inbound/outbound operation of the unit loads, that is, Single Command Cycle (SCC) and Double Command Cycle (DCC). In comparison, with the SCC mode, lift and shuttle-carrier can complete inbound operation of one unit loads and outbound operation of another unit loads in one travel. The equipment operation process is more complicated and more efficient. Therefore, this paper studied the configuration optimization problem of the system in DCC mode.

The following assumptions were considered in this paper:

(1) There is a lift in the middle of the unit multi-deep storage lanes; at each layer, there is a set of shuttle-carriers.

(2) In the initial state, the lifting platform is located at the I/O station, and the shuttle-carrier of each layer is located at the layer I/O point.

(3) The lift and the shuttle-carriers carry a unit loads at a time, and whether loading the unit load does not affect its moving speed.

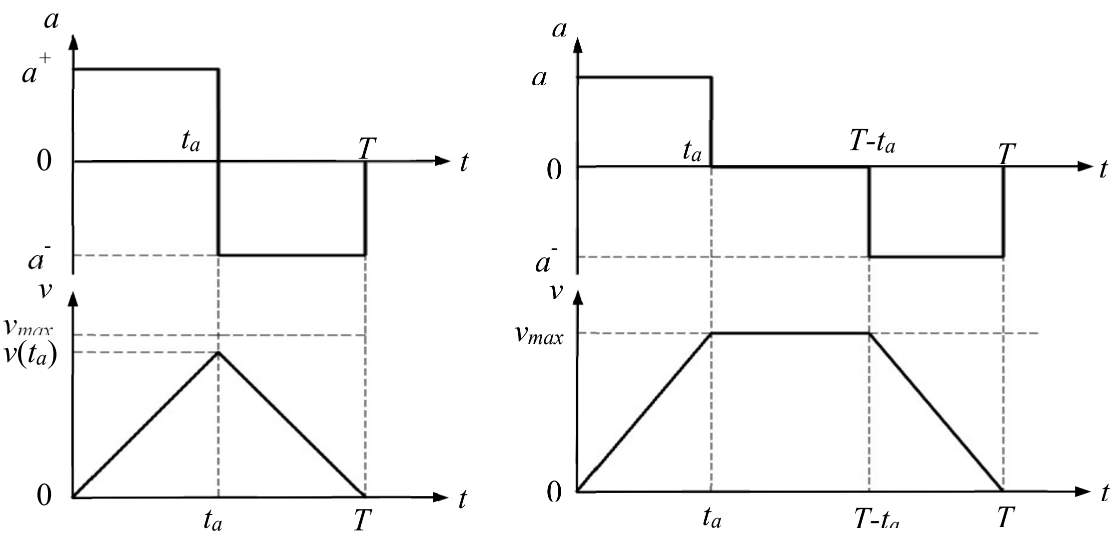
(4) The lift and shuttle have acceleration (deceleration) in motion. To simplify the model, it is assumed that the carrier is moving at a uniform speed.

(5) Under the principle of random storage, the probability that each empty storage location is selected is equal.

(6) Light loads are stored in the racks, regardless of the impact of weight on the model.

(7) The height and length of the unit storage rack are sufficient for the lifting platform and the shuttle to reach their maximum velocity.

The movement of the device can be simplified to uniform acceleration and uniform deceleration process [9-10]. According to whether the device movement reaches the maximum velocity during the moving, it is divided into two types of travel time models. Map of velocity-time relationship is shown in Figure 2.



(a)I-type travel time model (b)II- type of travel time model

Figure 2. Map of velocity-time relationship

a+ and a- respectively represent the acceleration and deceleration of the device movement. For the convenience of research, it is assumed that their value is equal to a. vmax represents the maximum moving velocity of the device, T represents the total time of the device travels, ta represents the time of acceleration, v(ta)indicates the peak velocity of the moving device at time ta. According to the velocity-time curve of the moving device, when the moving distance of the moving device is s, we have the following relationship:

$$T=\begin{cases} 2\sqrt{\dfrac{s}{a}} & (s<\dfrac{v_{\max}^2}{a}) \quad \text{I}-\text{type travel time model} \\ \dfrac{v_{\max}}{a}+\dfrac{s}{v_{\max}} & (s\geq\dfrac{v_{\max}^2}{a}) \quad \text{II}-\text{type travel time model} \end{cases} \tag{1}$$

3.2 Related Parameter Settings

The different three-dimensional dimensions of the racks and the setting of the motion parameters of the equipment will have different effects on the throughput, energy consumption and investment cost of the storage system. The throughput of the storage system refers to the amount of transactions stored

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or retrieved within a certain period of time, which is the inverse of the average throughput time. The average throughput time of the storage system is closely related to the operating efficiency of lift and shuttle-carrier. The faster the lift and shuttle-carrier speeds, the shorter the average throughput time of the system and the greater throughput of the system. In addition, the number of tiers, columns, and rows of unit storage rack also affect the average cycle time of the single system. In theory, more unit storage rack, shuttle-carrier, and smaller-sized unit racks will reduce the average throughput time of the system, but will increase more energy consumption and investment cost. The purpose of the model built in this paper is to find the trade-off between the average throughput time, total energy consumption and initial investment cost.

In this paper, when optimizing the configuration of the SCWS, the influence factors of the system are divided into two types: storage racks size configuration and equipment motion parameter setting. The detailed description is as follows:

(1) Storage racks size configuration

It includes the number of tiers, columns, rows of the unit storage rack and the number of unit storage rack. Cause each unit storage racks has a lift and each layer has a set of shuttle-carrier, the number of unit storage rack is equal to the number of lifts and the number of tiers is equal to the number of shuttle-carriers in one unit storage rack.

(2) Equipment motion parameters

Table 1. Basic parameter list of SCWS

Parameter	Symbol	Unit
length of the storage location(cell)	l	m
width of the storage location(cell)	w	m
height of the storage location(cell)	h	m
length of the unit storage rack	L	m
width of the unit storage rack	W	m
height of the unit storage rack	H	m
the number of tiers	M	level
the number of columns	C	column
the number of rows	A	row
the number of unit storage rack	N	piece
acceleration of the lifting platform	a_y	m/s^2
maximum velocity of the lifting platform	v_y	m/s
acceleration of the shuttle	a_x	m/s^2
maximum velocity of the shuttle	v_x	m/s
velocity of Carrier	v_z	m/s
times of shuttle loading/unloading carrier	t_{cr}	s
times of carrier loading/unloading the pallet	t_{zr}	s
times of the lifting platform loading/unloading the pallet	tsr	s
times of shuttle positioning	t_{cf}	s
times of carrier positioning	t_{zf}	s
times of lift positioning	t_{sf}	s

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It includes the maximum travel velocity for lift, shuttle and carrier, as well as the acceleration values for lift and shuttle.

In this paper, we used the M (number of tiers), C (number of columns), A (number of rows), N (number of the unit storage rack), ay (the acceleration of the lift), vy (the maximum velocity of the lift), ax (the acceleration of the shuttle), vx (the maximum velocity of the shuttle), vz (the velocity of the carrier) in the storage system as nine design variables. We presented a multi-objective function that minimizes the average throughput time, energy consumption, and investment cost of the storage system, and performed comprehensive optimization to find the optimal configuration.

The basic parameters of the storage rack in the system are shown in Table 1. At the same time, L=C·l, W=A·w, H=M·h.

4. Design Optimization Model of the SCWS

4.1 Minimize Average Throughput Time of SCWS

The average throughput time is the expected travel time required for the lifting platform and the shuttle-carrier to store or retrieve a unit loads. The mean cycle time(the average throughput time) could be minimized by minimizing expected dual command cycle time of lift and shuttle-carriers. The objective is to minimize the mean cycle time TRSCWS of the storage system, which is described as follows:

$$\min f_1\left(X\right) = \min TR_{\text{SCWS}}\left(M, C, A, N, v_x, v_y, a_x, a_y, v_z\right) \tag{2}$$

4.1.1 The Lifting Platform's Expected DCC Time

The lifting performs storage and retrieval processes at a time in DCC mode. A single complete DCC includes:(1)The lifting platform carries the unit loads from the I/O station to the i-level I/O point and puts the unit loads in the buffer area;(2) The lifting platform travels from the i-level I/O point to the j-level I/O point;(3) After loading the unit loads at j-level ,the lifting platform moves back to the I/O station(Figure 3, where (0, yi, 0) and (0, yj, 0) are the position coordinates of the i-level I/O point and the j-level I/O point, respectively.). According to the travelling of the lifting platform, travel time of lift for DCC consists of two the expected one-way travel times and one the expected travel-between time for two randomly selected tiers.

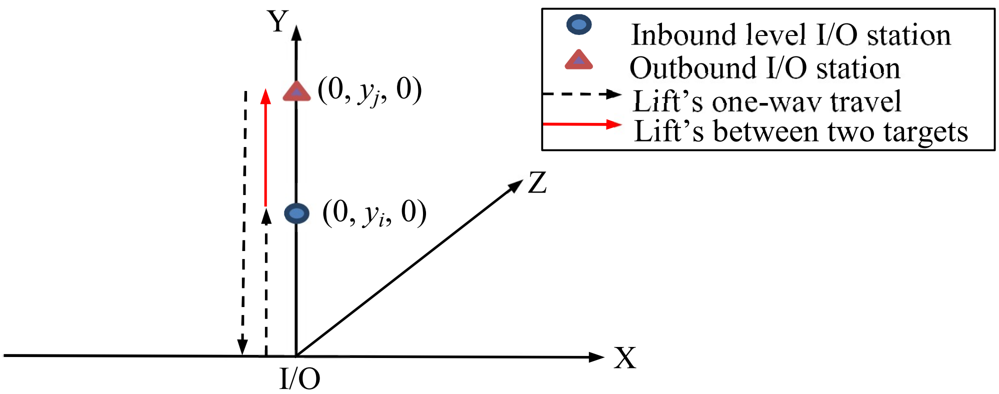

Figure 3. DCC operation procedure of the lift

(1) Lift's expected one-way travel time

One-way travel time of lifting platform corresponds to the variable travel time for travelling from the I/O station to any randomly selected the i-level I/O point (or from the i-level I/O point to the I/O

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station). Let P(y≤z) denote the probability that the one-way travel distance is less than or equal to z, Fys(z) denote the probability distribution function, fys(z) be the probability density function of z. The corresponding expression is shown by [11]:

$$F_{ys}\left(z\right)=P\left(y\leq z\right)=\begin{cases}\dfrac{z}{dy} & 0\leq z\leq dy\\ 1 & z>dy\end{cases} \tag{3}$$

$$f_{ys}\left(z\right)=\frac{dF_{ys}\left(z\right)}{dz}=\begin{cases}\dfrac{1}{dy} & 0\leq z\leq dy\\ 0 & z>dy\end{cases} \tag{4}$$

Let dy stands for travel distance of the lifting platform to the most distant tier in the SCWS. From Equation (1), the required time is calculated by: t(dy)=vy/ay+dy/vy. Therefore, the expected one-way travel time E(ST)lift of the lift is equal to the next expression:

$$E\left(ST\right)_{\text{lift}}=\frac{v_y}{a_y}+\frac{1}{v_y}\cdot\int_0^{dz}z\cdot f_{ys}\left(z\right)dz=\frac{v_y}{a_y}+\frac{dy}{2\cdot v_y} \tag{5}$$

(2) Lift’s the expected travel-between time for two tiers

It can be seen from Figure 5 that the travel distance between the two randomly selected tiers of the lifting platform is |yj-yi|. Let y(1), y(2), ..., y(n) are the order statistics of the samples y1, ..., yn in the vertical direction of the racks, then the difference of y(n)-y(1) is called the sample range R. Use P(|yj-yi|≤z) to indicate the probability that the distance between two points is less than or equal to z, that is, the probability of 0≤R≤z. The probability distribution function Fyd(z) between the two points and the probability density function fyd(z) is shown that [11]:

$$F_{yd}\left(z\right)=P\left(0\leq R\leq z\right)=\begin{cases}\dfrac{2\cdot z}{dy}-\dfrac{z^2}{dy^2} & 0\leq z\leq dy\\ 1 & z>dy\end{cases} \tag{6}$$

$$f_{yd}\left(z\right)=\frac{dF_{yd}\left(z\right)}{dz}=\begin{cases}\dfrac{z}{dy}-\dfrac{2\cdot z}{dy^2} & 0\leq z\leq dy\\ 0 & z>dy\end{cases} \tag{7}$$

Therefore, the expected travel-between time E(TB)lift between the two points of the lifting platform is equal to:

$$E\left(TB\right)_{\text{lift}}=\frac{v_y}{a_y}+\frac{1}{v_y}\cdot\int_0^{dy}z\cdot f_{yd}\left(z\right)dz=\frac{v_y}{a_y}+\frac{dy}{3\cdot v_y} \tag{8}$$

When the lifting platform performs storage and retrieval operation, in addition to the two one-way travel time and one travel-between time for two tiers, the lifting platform also execute four the load/unload times tsr and three the positioning times tsf.Therefore, the expected DCC travel time

E(DCC)lift for a complete dual command cycle of lifting platform when dy equals H, is calculated by:

$$E\left(DCC\right)_{\text{lift}} = 2\cdot E\left(ST\right)_{\text{lift}} + E\left(TB\right)_{\text{lift}} + 4\cdot t_{sr} + 3\cdot t_{sf} \tag{9}$$

$$E\left(DCC\right)_{\text{lift}} = \frac{3\cdot v_y}{a_y} + \frac{4\cdot H}{3\cdot v_y} + 4\cdot t_{sr} + 3\cdot t_{sf} \tag{10}$$

4.1.2 The Shuttle-carrier's Expected DCC Travel Time

The shuttle-carrier completes a storage operation and a retrieval operation under each dual command cycle. A single complete DCC includes:(1) The shuttle loads the carrier with the pallets and travel from the k-level I/O point to the i-column of this tier(travel form(0, yk, 0)to (xi, yk, 0));(2) the shuttle releases the fully loaded carrier, then the carries transport the pallets from i-column port to the m-row storage position along the storage lane(travel form(xi, yk, 0)to (xi, yk, zm)); 3) the carrier unloads the pallets to the storage position, it returns to i-column port at the original route(travel form (xi, yk, zm) to (xi, yk, 0));(4) the shuttle reloads carrier and drives to the j-column port(travel form (xi, yk, 0) to(xj, yk, 0));(5) the shuttle releases the carrier, then the carries travels to the n-row retrieval position of j-column (travel form (xj, yk, 0) to(xj, yk, zn));(6) The carrier loads the pallets back to the j-column port along the original route(travel form (xj, yk, zn) to (xj, yk, 0));(7) The shuttle loads the carrier with the pallets and returns from j-column port to the k-level I/O point and puts the pallets in the buffer area (travel form(xj, yk, 0)to (0, yk,0)). The specific DCC operation procedure of the shuttle-carrier is shown in Figure 4.

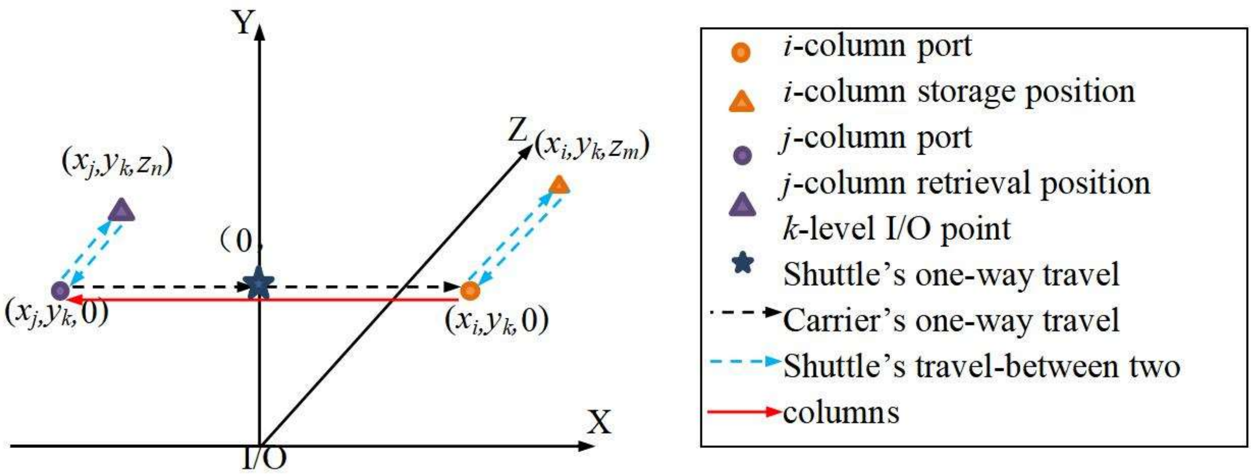

Figure 4. DCC operation procedure of the shuttle-carrier

According to the travelling of the shuttle-carrier, DCC travel time of shuttle-carrier consists of two shuttle's one-way travel times, one travel-between time for two randomly selected columns and four Carrier's one-way travel times.

(1) Shuttle's one-way expected travel time

Because the layer I/O point is located in the middle of the storage racks, the maximum one-way travel distance of the shuttle does not exceed 1/2 of the rack length, but the maximum distance between the two columns is the rack length. Letting dx denote the Travel distance of the shuttle to the most distant column in the SCWS, from Equation(1), the required time is calculated by t(dx)=vx/ax+dx/vx.

Let P(x≤m) denote the probability that the shuttle's one-way travel distance is less than or equal to m when the shuttle moves from the layer I/O point to i-column port (or from j-column port to the layer

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I/O point). The valid range of m is 0≤m≤0.5dx. Let Fxs(m) denote the probability distribution function of m, and fxs(m) be the probability density function of m. The following expression is obtained:

$$F_{xs}(m)=P(x\le m)=\begin{cases}\dfrac{m}{dx} & 0\le m\le 0.5dx\\ 1 & m>0.5dx\end{cases} \tag{11}$$

$$f_{xs}(m)=\frac{dF_{xs}(m)}{dm}=\begin{cases}\dfrac{1}{dx} & 0\le m\le 0.5dx\\ 0 & m>0.5dx\end{cases} \tag{12}$$

Therefore, the expected one-way travel time E(ST)x_shuttle of the shuttle is calculated by:

$$E(ST)_{x\_\text{shuttle}}=\frac{v_x}{a_x}+\frac{1}{v_x}\cdot\int_0^{0.5dx} m\cdot f_{xs}(m)dm=\frac{v_x}{a_x}+\frac{dx}{8\cdot v_x} \tag{13}$$

(2) Carrier's expected one-way travel time

The carrier travels at a constant speed in the storage lane. Letting dz represents the travel distance of the carrier in the storage lane, hence the travel time is t(dz)=dz/vz.

Let P(z≤p) denote the probability that the one-way travel distance is less than or equal to p. Then, probability distribution function Fz(p), the probability density function fz(p) are shown by:

$$F_z(p)=P(z\le p)=\begin{cases}\dfrac{p}{dz} & 0\le p\le dz\\ 1 & p>dz\end{cases} \tag{14}$$

$$f_z(p)=\frac{dF_z(p)}{dp}=\begin{cases}\dfrac{1}{dz} & 0\le p\le dz\\ 0 & p>dz\end{cases} \tag{15}$$

Therefore, the expected one-way time E(ST)z_carrier of the carrier is calculated by:

$$E(ST)_{z\_\text{carrier}}=\frac{1}{v_z}\cdot\int_0^{dz} p\cdot f_z(p)dp=\frac{dz}{2\cdot v_z} \tag{16}$$

(3) Shuttle's the expected travel-between time for two columns

It can be seen from Figure 6 that the travel distance between the two randomly selected columns of the shuttle is |xj-xi|. P(|xj-xi|≤m) represents the probability that the travel distance between the two points is less than or equal to m, where the valid range of m is 0≤m≤0.5dx or 0.5dx≤m≤dx. The probability distribution function Fxd(m) and the probability density function fxd(m) is calculated by [12]:

$$F_{xd}(m)=\begin{cases}\dfrac{m}{dx}-\dfrac{m^2}{4\cdot dx^2} & 0\le m\le 0.5dx\\ \dfrac{m}{dx}-\dfrac{3\cdot m^2}{4\cdot dx^2} & 0.5dx<m\le dx\\ 1 & m>dx\end{cases} \tag{17}$$

$$f_{xd}(m)=\begin{cases}\dfrac{1}{dx}-\dfrac{m^2}{2\cdot dx^2} & 0\le m\le 0.5dx\\ \dfrac{1}{dx}-\dfrac{3\cdot m^2}{2\cdot dx^2} & 0.5dx<m\le dx\\ 0 & m>dx\end{cases} \tag{18}$$

Therefore, the expected travel-between time E(TB)shuttle between the two points of the shuttle is obtained:

$$E(TB)_{\text{shuttle}}=\frac{v_x}{a_x}+\frac{1}{v_x}\int_0^{dx} m\cdot f_{xd}(m)dm=\frac{v_x}{a_x}+\frac{dx}{24\cdot v_x} \tag{19}$$

When the shuttle-carrier performs the storage and retrieval operation, in addition to the two shuttle's one-way travel times, one travel-between time for two randomly selected columns and four carrier's one-way travel times, the shuttle-carrier also execute four the times of shuttle loading/unloading carrier tcr, two the times of carrier loading/unloading the pallet tzr, three times of shuttle positioning tcf and four times of carrier positioning tzf. Therefore, the expected DCC travel time E(DCC)shuttle for a complete dual command cycle of the shuttle-carrier when dx equals L and dz equals W, is calculated by:

$$\begin{aligned}E(DCC)_{\text{shuttle}}&=2\cdot E(ST)_{x\_\text{shuttle}}+4\cdot E(ST)_{z\_\text{carrier}}+E(TB)_{\text{shuttle}}\\&+4\cdot t_{cr}+2\cdot t_{zr}+3\cdot t_{cf}+4\cdot t_{zf}\end{aligned} \tag{20}$$

$$E(DCC)_{\text{shuttle}}=\frac{3\cdot v_x}{a_x}+\frac{7\cdot L}{24\cdot v_x}+\frac{2\cdot W}{v_z}+4\cdot t_{cr}+2\cdot t_{zr}+3\cdot t_{cf}+4\cdot t_{zf} \tag{21}$$

4.1.3 Average Throughput Time of SCWS

In the SCWS, the lift and the multi-layer shuttle-carrier simultaneously move to complete storage and retrieval operations. The expected DCC travel time E(DCC)SCWS for the unit storage system is the maximum of both the expected travel time of the lift and the expected travel time of single-layer shuttle-carrier. Based on assumption, there are M sets of shuttle-carriers that can work simultaneously and a lift in the unit storage system. Hence, the expected DCC travel time E(DCC)SCWS for the unit storage system is calculated by:

$$E(DCC)_{\text{SCWS}}=\max\left(E(DCC)_{\text{lift}},\frac{E(DCC)_{\text{shuttle}}}{M}\right) \tag{22}$$

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Therefore, the average throughput time TRSCWS of the entire storage system is calculated by expression (23):

$$TR_{\mathrm{SCWS}}=\frac{E\left(DCC\right)_{\mathrm{SCWS}}}{k\cdot N} \tag{23}$$

Where k is 2, due to the DCC and N represents the number of unit storage racks.

4.2 Minimize Energy Consumption of SCWS

Long-term high-load operation of lift and shuttle-carrier results in high energy consumption. In this paper, the influence of the motion parameters of lift and shuttle-carrier on energy consumption is analyzed, and the minimize energy consumption model ECSCWS of SCWS is established. The objective is shown as follows:

$$\min f_2\left(X\right)=\min EC_{\mathrm{SCWS}}\left(M,C,A,N,v_x,v_y,a_x,a_y,v_z\right) \tag{24}$$

The motor provides the traction (or braking force) required for lift and shuttle-carrier motion, whereby the engine power can be calculated accordingly. The engine power is calculated as shown in Equation (25):

$$P=\frac{F_T\cdot v}{1000\cdot\eta} \tag{25}$$

Where: v represents maximum velocity of the equipment (m/s);ηrepresents equipment operating efficiency; FT represents traction or braking force (N).

The following sections introduce calculations for the required engine power Py of the lifting platform (considering the power in acceleration, constant velocity and deceleration) [13], the required engine power Px of the shuttle and the required engine power Pz of carrier.

4.2.1 Required Engine Power of the Lift

Thanks to the application of energy recovery technology, when the lifting platform falls vertically, its energy regeneration module can generate electricity, which can effectively reduce the energy consumption [14]. But When the lifting platform rises vertically, the motor supplies power. So this paper mainly calculates the power when the lifting platform rises vertically. The mean required power of the lifting platform Py when travel distance equals H , is calculated by:

$$P_y=\sqrt{\frac{p_{yTa}^2\cdot t_{ya}+p_{yTv}^2\cdot t_{yv}+p_{yTb}^2\cdot t_{yb}}{t_{ya}+t_{yv}+t_{yb}}} \tag{26}$$

where:

$$P_{yTa}=\frac{\left(m_y\cdot a_y\cdot k_{ir}+m_y\cdot g\right)\cdot v_y}{1000\cdot\eta_{\mathrm{lift}}} \tag{27}$$

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$$P_{yTv} = \frac{m_y \cdot g \cdot v_y}{1000 \cdot \eta_{\text{lift}}} \tag{28}$$

$$P_{yTb} = \frac{\left(m_y \cdot a_y \cdot k_{ir} - m_y \cdot g\right) \cdot v_y}{1000 \cdot \eta_{\text{lift}}} \tag{29}$$

$$t_{ya} = t_{yb} = \frac{v_y}{a_y} \tag{30}$$

$$t_{yv} = \frac{H}{v_y} - \frac{v_y}{a_y} \tag{31}$$

In these expressions: PyTa(kw) indicates the engine power of the lifting platform during acceleration, PyTv (kw) indicates the engine power of the lifting platform in case of travelling with constant velocity, PyTb(kw) indicates the engine power of the lifting platform during deceleration, tya(s) indicates time for acceleration of the lifting platform to reach its maximum velocity vy, tyv(s) indicates the time for travelling of the lifting platform with constant velocity, tyb(s) indicates the time for deceleration of the lifting platform, my(kg) indicates mass of the lifting platform with loads, ay (m/s2) indicates acceleration of the lifting platform, g(m/s2) indicates acceleration of gravity, kir indicates rotational mass conversion factor, ηlift indicates efficiency of lift.

4.2.2 Required Engine Power of the Shuttle

The mean energy of the shuttle moving on the main track Px when travel distance equals L ,is calculated by:

$$P_{\text{x}} = \sqrt{\frac{p_{xTa}^2 \cdot t_{xa} + p_{xTv}^2 \cdot t_{xv} + p_{xTb}^2 \cdot t_{xb}}{t_{xa} + t_{xv} + t_{xb}}} \tag{32}$$

where:

$$P_{xTa} = \frac{(m_x \cdot a_x \cdot k_{ir} + m_x \cdot g \cdot k_r) \cdot v_x}{1000 \cdot \eta_{x\_\text{shuttle}}} \tag{33}$$

$$P_{xTv} = \frac{m_x \cdot g \cdot k_r \cdot v_x}{1000 \cdot \eta_{x\_\text{shuttle}}} \tag{34}$$

$$P_{xTb} = \frac{(m_x \cdot a_x \cdot k_{ir} - m_x \cdot g \cdot k_r) \cdot v_x}{1000 \cdot \eta_{x\_\text{shuttle}}} \tag{35}$$

$$t_{xa} = t_{xb} = \frac{v_x}{a_x} \tag{36}$$

$$t_{xv} = \frac{L}{v_x} - \frac{v_x}{a_x} \tag{37}$$

In these expressions: PxTa (kw) indicates the engine power of the shuttle during the acceleration, PxTv (kw) indicates the engine power of the shuttle in case of travelling with constant velocity, PxTb (kw) indicates the engine power of the shuttle during deceleration, txa (s) indicates time for acceleration of the shuttle to reach its maximum velocity vx, txv (s) indicates the time for travelling of the shuttle with constant velocity, txb (s) indicates the time for deceleration of the shuttle, mx (kg) indicates mass of the shuttle with loads, ax (m/s2) indicates acceleration of the shuttle, kr indicates rolling resistance coefficient, ηx_shuttle indicates efficiency of shuttle.

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4.2.3 Required Engine Power of the Carrier

Cause the carrier always travels with constant velocity in the storage lane, traction force FzTv (N) is equal to the rolling resistance Fzf (N), that is, FzTv=Fzf= Gz·kr. Therefore, the required engine power Pz (kw) of the carrier is calculated by:

$$P_z = \frac{F_{zTv} \cdot v_z}{1000 \cdot \eta_{z\_\mathrm{carrier}}} = \frac{G_z \cdot k_r \cdot v_z}{1000 \cdot \eta_{z\_\mathrm{carrier}}} \tag{38}$$

where: Gz (N) indicates total gravity of carrier with loads (Gz=mz·g), ηz_carrier indicates efficiency of carrier.

4.2.4 Total Energy Consumption of SCWS

In summary, the total power P(kw) of the M sets of shuttle-carrier and a lift in the unit storage system is represented by the following expression:

$$P = \left(P_x + P_z\right) \cdot M + P_y \tag{39}$$

Therefore, the annual energy consumption of the entire SCWS ECSCWS (kw·h/year) is calculated by:

$$EC_{SCWS} = P \cdot N \cdot T_{shift} \cdot n_{wd} \cdot n_{weeks} \cdot \eta_{SCWS} \tag{40}$$

where: Tshift indicates number of working hours of unit storage system in a day, nwd indicates number of working days in a week, nweeks indicates number of weeks in a year, ηSCWS indicates efficiency of SCWS. In practice, the energy consumption is equal to the integral of the power consumption over time. We assumed that this simplified expression is good enough for our research.

4.3 Minimize Total Cost of SCWS

The cost definition of the SCWS mainly consist of:

(1) The investment for equipment ISL (RMB): the cost of purchasing a certain amount of lift and shuttle-carrier.

(2) The investment for the storage racks ISR (RMB): the cost of building the storage racks.

(3) The investment for the storage area of SCWS in a year ISA (RMB/year).

(4) The cost for energy consumption of SCWS in a year IEC (RMB/year).

Total cost is closely related to throughput time and energy consumption. The use of a large number of high-efficiency handling equipment like lifts and shuttle-carriers will reduce throughput time, but will undoubtedly increase the investment for equipment and electricity consumption in the storage system. Therefore, this paper established a minimum total cost model TCSCWS. The objective is shown as follows:

$$\min f_3\left(X\right) = \min TC_{\mathrm{SCWS}}\left(M, C, A, N, v_x, v_y, a_x, a_y, v_z\right) \tag{41}$$

The total cost of the entire SCWS TCSCWS (RMB) is calculated by:

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$$TC_{\mathrm{SCWS}} = I_{\mathrm{SL}} + I_{\mathrm{SR}} + T_P \cdot \left(I_{\mathrm{SA}} + I_{\mathrm{EC}}\right) \tag{42}$$

where, TP is the expected life time of the SCWS. And,

$$I_{\mathrm{SL}} = \left(C_{\mathrm{lift}} + M \cdot C_{\mathrm{s\text{-}c}}\right) \cdot N \tag{43}$$

$$I_{\mathrm{SR}} = C_{\mathrm{SR}} \cdot M \cdot C \cdot A \cdot N \tag{44}$$

$$I_{\mathrm{SA}} = C_{\mathrm{SA}} \cdot L \cdot W \cdot N \tag{45}$$

$$I_{\mathrm{EC}} = C_{\mathrm{EC}} \cdot EC_{\mathrm{SCWS}} \tag{46}$$

In these expressions: Clift (RMB/unit) indicates the cost of a lift, Cs-c indicates the cost of a set of shuttle-carrier (RMB/set), CSR indicates the cost of a storage position (cell) (RMB/unit), CSA (RMB/m2·year) indicates the cost of storage area per square meter year, CEC (RMB/kw·h) indicates the cost for 1 kWh of electricity, ECSCWS (kw·h/year)indicates the annual energy consumption of the entire SCWS.

4.4 Multi-objective Optimization Model of SCWS

When designing the SCWS, we considered three objectives of minimizing average throughput time, minimizing energy consumption, and minimizing total cost. It is a Multi-objective Optimization Problem (MOP).The multi-objective optimization model of SCWS is described as follows:

$$\begin{aligned} &\min f\left(X\right) = \min\left\{f_1\left(X\right), f_2\left(X\right), f_3\left(X\right)\right\}; \\ &\text{s.t.} \begin{cases} Q_{\min} - Q\left(X\right) \le 0; \\ X_l \le X \le X_u; \\ X = \left\{M, C, A, N, v_x, v_y, a_x, a_y, v_z\right\}. \end{cases} \end{aligned} \tag{47}$$

where: f1(X) is the average throughput time function of the SCWS, f2(X) is the energy consumption function of the SCWS, and f3(X) is the total cost function of the SCWS. The size of the SCWS is determined by the number of tiers M, the number of columns C the number of rows A and he number of unit storage rack N in such a way that the optimization constraint in terms of Q. This paper sets the minimum the volume of the SCWS that meets the needs of the enterprise in terms of Qmin = 15000 cells. And This paper sets the design space bounds of each decision variable X, that is, it must belong between the upper bound Xl and the lower bound Xu.

4.5 Solution Algorithm

Important decision-making problems in real life basically need to consider optimizing multiple goals under different constraints, and these goals are often coupled together in a "strong and weak" state. The optimization objective involved in the configuration optimization of the SCWS also needs to consider this kind of inverse relationship. Therefore, this section will use a multi-objective optimization method to solve the configuration optimization model.

Deb et al. [15] proposed a Pareto multi-objective optimization approach, non-dominated sorting genetic algorithm with an elite strategy (NSGA-II), to solve multi-objective optimization problems. Due to the non-linearity of the multi-objective, Matej Borovinšek et al. [16] used NSGA-II to solve the multi-objective design problem of shuttle-based storage and retrieval system. The NSGA-II algorithm has significant advantages in solving multi-objective problems. And it is able to find out the an uncountable number of solutions (Pareto optimal solutions). Specifically, this paper utilized

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NSGA-II algorithm to obtain the Pareto optimal solution, which is provided to the warehouse designer. Finally the designer determines to choose an acceptable solution from all Pareto solutions. Figure 5 presents the detailed flow diagram of NSGA-II.

5. Numerical Experiments and Optimization Results

In this section, the numerical experiment of the different configurations of the shuttle-carrier warehouse system is presented. This paper designs and conducts numerical experiments and optimization based on the equipment parameters of the SCWS provided by a material handling equipment supplier and the actual operation data provided by a pharmaceutical logistics distribution center.

The warehouse minimum volume is Qmin=15000. The average mass of the unit loads is m=200kg. According to the characteristics of the stored items, the logistics distribution center intends to use the AS-RL-200 reciprocating lift and the RGV-1000 (L) type shuttle-carrier produced by the equipment supplier. Additional constant parameters are shown in Table 2.

The overall size of SCWS is determined by the number of tiers, columns, rows of the unit storage racks and the number of unit storage rack. In theory, the smaller the system size, the better the three objective function values in the configuration optimization model. In order to meet the warehouse minimum volume Qmin constraints, it is necessary to numerically constrain the size of the unit storage rack. According to actual experience of the authors and the references of the equipment supplier, the value range of decision variables is selected as shown in Table 3.

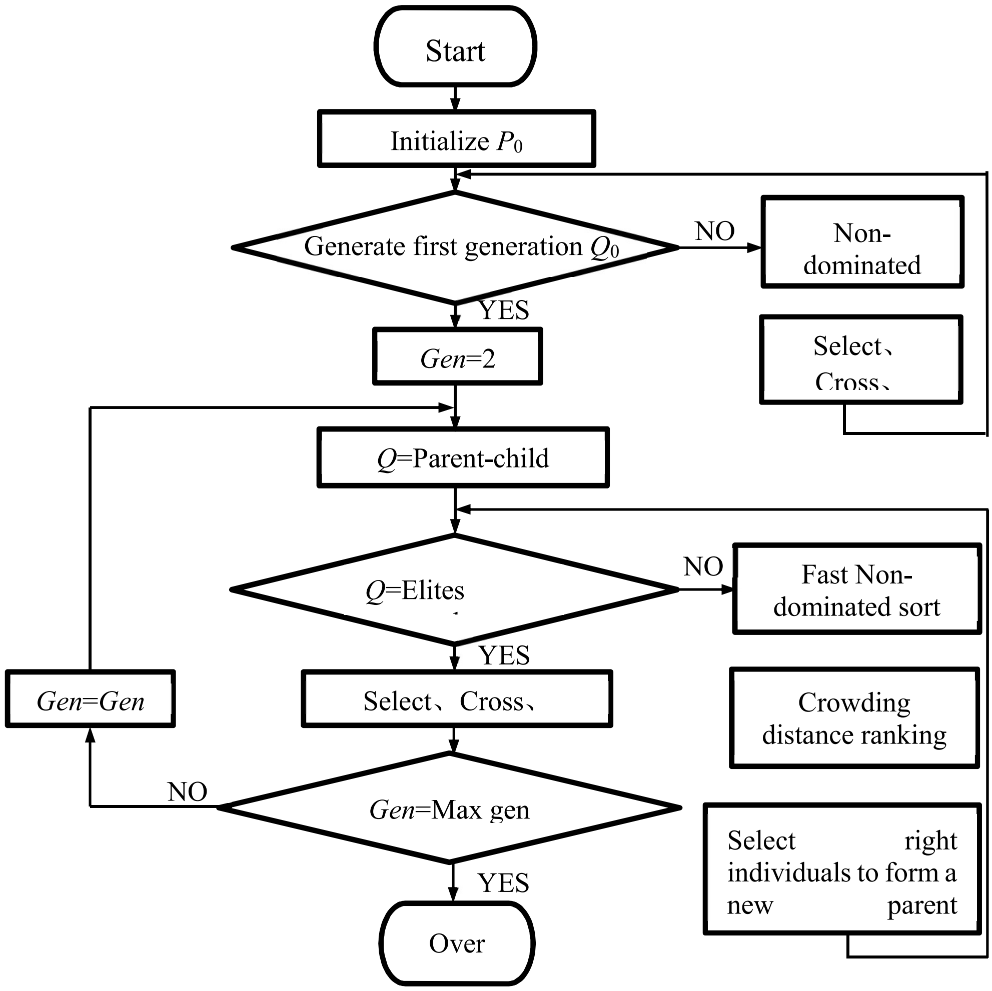

Figure 5. Flow diagram of NSGA-II

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Table 2. Constant parameters used for calculation

Parameter	Symbol	Value
length of the storage location(cell)	l	1.3m
width of the storage location(cell)	w	1.1m
height of the storage location(cell)	h	1.2m
times of shuttle loading/unloading carrier	t_{cr}	0.8s
times of carrier loading/unloading the pallet	t_{zr}	1.2s
times of the lifting platform loading/unloading the pallet	t_{sr}	2.0s
times of shuttle positioning	t_{cf}	0.5s
times of carrier positioning	t_{zf}	0.5s
times of lift positioning	t_{sf}	0.5s
mass of carrier with loads	m_z	428kg
mass of the shuttle with loads	m_x	718kg
mass of the lifting platform with loads	m_y	490kg
acceleration of gravity	g	9.8m/s^2
rotational mass conversion factor	k_{ir}	1.15
rolling resistance coefficient	k_r	0.01
efficiency of carrier	$\eta_{z\_\mathrm{carrier}}$	0.9
efficiency of shuttle	$\eta_{x\_\mathrm{shuttle}}$	0.9
efficiency of lift	η_{lift}	0.9
efficiency of SCWS	η_{SCWS}	0.8
the cost of a set of shuttle-carrier	$C_{\mathrm{s\text{-}c}}$	300,000 RMB/Set
the cost of a lift	C_{lift}	500000 RMB/unit
the cost of a storage position (cell)	C_{SR}	300 RMB/unit
the cost of storage area per square meter year	C_{SA}	240 RMB/m^2·year
the cost for 1 kWh of electricity	C_{EC}	0.8 RMB/kw·h
number of working hours of unit storage system in a day	T_{shift}	16 hours
number of working days in a week	n_{wd}	5 days
number of weeks in a year	n_{weeks}	50 weeks
expected life time of the SCWS	T_P	10 years

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Table 3. The value range of decision variables parameters

Parameter	Meaning	Unit	Min value	Max value
M	number of tiers	Layer	1	16
C	number of columns	Column	1	60
A	number of rows	Row	1	30
N	number of unit storage rack	Piece	1	5
vx	maximum velocity of the shuttle	m/s	1.5	3.0
vy	maximum velocity of the lifting platform	m/s	1.0	2.0
ax	acceleration of the shuttle	m/s2	0.5	1.5
ay	acceleration of the lifting platform	m/s2	0.5	1.0
vz	velocity of Carrier	m/s	1.0	2.0

This paper used MATLAB R2016b to solve the multi-objective optimization model. The study used NSGA-II and ran it on a personal computer with an Intel Core i5-7200U CPU. The parameter settings of the NSGA-II algorithm are shown in Table 4. After 200 generations, the Pareto optimal solution front of the configuration optimization problem of SCWS is presented in Figure 6.

The Pareto front of configuration optimization problem in Figure 6 obtained by the NSGA-II algorithm is approximated as a smooth curve. And the Pareto solution set has a wide and uniform distribution. Therefore, each solution in the Figure 6 is the Pareto optimal SCWS configurations.

Table 4. Paramenters values of NSGA-II

Parameter	Meaning	Value
P	the size of population	100
Gen	the number of generations	200
Pc	the degree of crossover	0.9
Pm	the degree of mutation	0.1

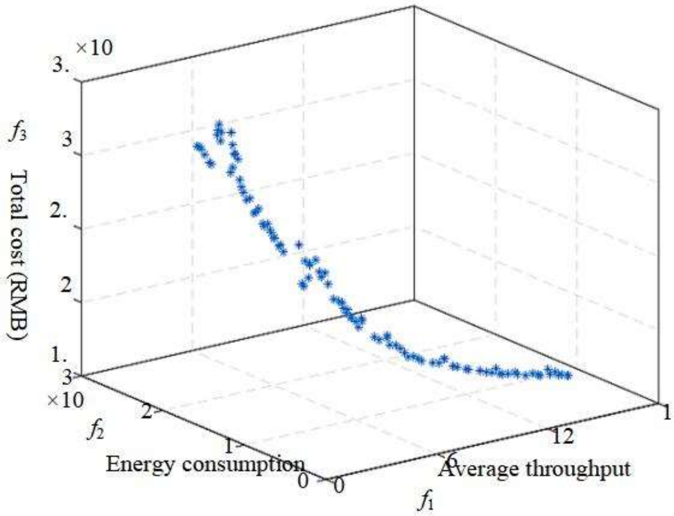

Figure 6. The Pareto optimal solution front after 200 generations

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6. Analyses and Evaluation of Simulation Results

Table 5. Pareto solutions sorted by average throughput time

Num.	M	C	A	N	v_x (m/s)	v_y (m/s)	a_x (m/s^2)	a_y (m/s^2)	v_z (m/s)	TR_{SCWS} (s)	EC_{SCWS} (10^3kw·h)	TC_{SCWS} (million yuan)
1	4	42	25	5	1.5	1.4	1.3	1.0	2.0	1.83	163.59	33.1486
2	5	42	25	5	1.5	1.4	1.4	1.0	2.0	1.86	163.00	33.4725
3	5	42	25	5	1.5	1.4	1.4	1.0	2.0	1.88	159.02	32.6112
4	5	39	25	5	1.5	1.5	1.5	1.0	2.0	1.94	166.75	32.5116
5	4	41	29	5	1.5	1.0	1.3	0.8	1.2	1.95	121.26	35.2408
6	4	41	29	5	1.5	1.0	1.3	0.8	1.2	1.95	121.21	34.9590
7	4	38	28	5	1.5	1.0	1.3	0.8	1.3	1.96	131.64	33.6077
…	…	…	…	…	…	…	…	…	…	…	…	…
95	13	60	26	1	1.5	1.3	0.7	0.7	1.7	15.49	49.89	16.1376
96	14	60	26	1	1.5	1.3	0.7	0.7	1.7	15.80	49.19	16.0840
97	14	60	26	1	1.5	1.2	0.7	0.7	1.7	15.82	49.26	16.0709
98	15	56	26	1	1.6	1.4	0.8	0.6	1.6	16.55	57.89	16.0684
99	15	55	26	1	1.5	1.3	0.9	0.5	1.5	17.23	52.19	16.0161
100	15	55	26	1	1.5	1.3	0.9	0.5	1.5	17.33	52.01	16.0130

Table 6. Pareto solutions sorted by energy consumption

Num.	M	C	A	N	v_x (m/s)	v_y (m/s)	a_x (m/s^2)	a_y (m/s^2)	v_z (m/s)	TR_{SCWS} (s)	EC_{SCWS} (10^3kw·h)	TC_{SCWS} (million yuan)
1	14	60	26	1	1.5	1.3	0.7	0.7	1.7	15.80	49.19	16.0840
2	14	60	26	1	1.5	1.2	0.7	0.7	1.7	15.82	49.26	16.0709
3	13	60	26	1	1.5	1.3	0.7	0.7	1.7	15.49	49.89	16.1376
4	14	60	26	1	1.5	1.4	0.7	0.7	1.8	15.16	50.94	16.1133
5	14	60	26	1	1.5	1.4	0.8	0.8	1.7	14.63	51.07	16.1040
6	15	55	26	1	1.5	1.3	0.9	0.5	1.5	17.33	52.01	16.0130
7	15	55	26	1	1.5	1.3	0.9	0.5	1.5	17.23	52.19	16.0161
…	…	…	…	…	…	…	…	…	…	…	…	…
96	6	41	21	4	2.0	1.6	0.8	1.0	1.2	2.31	247.66	29.6751
97	6	39	21	4	2.0	1.6	0.8	1.0	1.2	2.34	253.82	29.5385
98	6	39	21	4	2.0	1.6	0.7	1.0	1.2	2.27	257.62	30.2294
99	6	40	21	5	2.0	1.6	0.8	1.0	1.2	2.19	259.80	30.8743
100	6	39	21	4	2.0	1.6	0.8	1.0	1.2	2.25	261.60	30.4772

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Table 7. Pareto solutions sorted by total cost

Num.	M	C	A	N	v_x (m/s)	v_y (m/s)	a_x (m/s^2)	a_y (m/s^2)	v_z (m/s)	TR_{SCWS} (s)	EC_{SCWS} (10^3kw·h)	TC_{SCWS} (million yuan)
1	15	55	26	1	1.5	1.3	0.9	0.5	1.5	17.33	52.01	1601.30
2	15	55	26	1	1.5	1.3	0.9	0.5	1.5	17.23	52.19	1601.61
3	15	56	26	1	1.6	1.4	0.8	0.6	1.6	16.55	57.89	1606.84
4	14	60	26	1	1.5	1.2	0.7	0.7	1.7	15.82	49.26	1607.09
5	14	60	26	1	1.5	1.3	0.7	0.7	1.7	15.80	49.19	1608.40
6	14	60	26	1	1.5	1.4	0.8	0.8	1.7	14.63	51.07	1610.40
7	14	60	26	1	1.5	1.4	0.7	0.7	1.8	15.16	50.94	1611.33
…	…	…	…	…	…	…	…	…	…	…	…	…
96	4	40	28	5	1.5	1.0	1.3	0.7	1.2	2.04	123.62	3401.59
97	4	41	29	5	1.5	1.0	1.3	0.8	1.2	1.99	118.78	3445.12
98	4	41	29	5	1.5	1.0	1.3	0.8	1.2	1.95	121.21	3495.90
99	4	41	29	5	1.5	1.0	1.3	0.8	1.2	1.95	121.26	3524.08
100	4	42	29	5	1.5	1.0	1.3	0.8	1.2	1.97	120.16	3572.36

Using the NSGA-II algorithm with Elite Strategy, 100 Pareto optimal solution sets were obtained. Each solution set is an alternative configuration design, and the objective function values obtained by each solution are different. The different values of the decision variables will make the average throughput time, energy consumption and total cost of the SCWS different.

The following is a more detailed description of how to choose different configurations according to the needs of the enterprise. The solutions are sorted by three objective function values in turn, and the results are displayed in three differently sorted tables. The SCWS configurations ranking results are respectively shown in Table 5, Table 6, and Table 7, according to the increasing direction of the average throughput time TRSCWS, energy consumption ECSCWS, and total cost TCSCWS. Due to the excessive amount of data, it is not possible to list them one by one. The solutions in the middle of each list were excluded from the table.

Table 5 presents that when solutions were sorted by average throughput time in the increasing direction, throughput time of the optimal solution is 1.83 s, which is about 1/10 of the maximum average throughput time. The optimal configuration has 4 tiers and 5 unit storage racks, that is, 5 lifts and 20 sets of shuttle-carriers. And the storage area of SCWS is 7507.5 m2. Therefore, the configuration is applicable to a traditional low-rise warehouse with a large area, and does not require more three-dimensional space.

Table 6 presents that when solutions were sorted by annual energy consumption in an increasing manner, energy consumption of the optimal solution is 49190kw·h/year, which is about 1/5 of the maximum energy consumption. However, the average throughput time at the lowest energy consumption is 15.80 seconds, which is 8.6 times slower than the optimal solution in Table 5.

Table 7 presents that when configurations were sorted by total cost of the SCWS in the increasing manner, the total cost of the optimal solution is 16.013 million yuan, while the cost of the most expensive configuration solution is 35.372 million yuan. That is to say, the cost of additional expenditure in 10 years is about 20 million yuan. However, the minimum total cost configuration has an average throughput time of 17.33 s, which is 9.4 times slower than the fastest solution in Table 5.

The above analysis shows that the equipment configuration of high-efficiency operation will inevitably lead to high energy consumption and high investment cost. In recent years, many equipment manufacturers have also produced a large number of high-speed equipment. But is the device operation in the warehousing system as fast as possible? This also requires deeper thinking. Throughput time of the storage system under a reasonable configuration may not be the shortest, but moderate investment and energy consumption may be more significant for enterprises and society.

7. Conclusion

This paper studies the configuration optimization problem of Shuttle-Carrier Warehousing System(SCWS). Considering the inverse relationship between system operation efficiency, energy consumption and cost, the SCWS dimensions (A, C, M, N) and equipment physical parameters (vx, vy, ax, ay, vz) are analyzed and selected. A multi-objective optimization model was established with minimum average throughput time, minimum energy consumption, and minimum total cost. In this study, the multi-objective optimization model was solved by NSGA-II algorithm with Elite Strategy, and the Pareto optimal solution was obtained within a single simulation run. The size of the storage racks and equipment motion parameters were comprehensively and reasonably configured. The mathematical model and solution proposed in this paper can provide useful reference for enterprise designers to implement the initial design of the warehouse system.

In this paper, we have set up a shuttle-carrier on each level, regardless of the cross-layer operation of the shuttle-carrier. In future work, the study can be extended to the configuration optimization of warehouse system with shuttles cross-layer operations.

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