Modeling and Analysis for Inherent Energy Efficiency of Two-machine Bernoulli Serial Lines

Longyao Xu, Peiji Liu, *Member, IEEE*, Xu Wang, Fangyuan Yu and Chao Liu, *Member, IEEE*

Abstract—**In recent years, the topic of balancing the energy efficiency of production systems with production performance parameters such as productivity and buffer capacity has received increasing attention. However, the existing research generally focuses on the operational energy efficiency of the production system, which may changes with various workpieces and make it difficult to support the formation and optimization of high-efficiency production lines. For this reason, we firstly propose the inherent energy efficiency of production systems to describe the common characteristics of the operational energy efficiency that do not vary with workpiece changes when production systems machining various possible future workpieces. Secondly, the specific inherent energy efficiency model which based on the unreliability of the production unit and the limited capacity of the product buffer of the Bernoulli two-machine serial production system has been established. Then a mathematical analysis method oriented to the optimal solution for the production line buffer capacity and the inherent energy efficiency has been proposed. Finally, numerical analysis is used to verify that the models and methods proposed in this paper are instructive for energy-efficient design and upgrading of production systems.**

I. Introduction

In recent years, due to the increasingly serious energy costs and environmental problems, the study of energy efficiency of production systems has become an important strategy for realizing green manufacturing due to its high energy consumption and outstanding energy saving and carbon reduction benefits[1-2]. However, as the energy consumption of the production system decreases, the productivity will be negatively affected to a certain extent, so the balanced optimization research of energy consumption and productivity is particularly important and has been extensively studied[3-4].

Previous research of the balance between energy consumption and productivity mainly consists of two aspects: on-off control of single machine and multi-machine. In terms of single machine, Shrouf et al.[5] solved the mathematical model for minimizing single-machine scheduling energy consumption through genetic algorithm; In terms of multi-machine, Mashaei et al. [6] reduces the energy consumption of the pallet constraint production line by designing a on-off control strategy for idle machines, Frigerio et al. [7-8] performs on-off control of equipment based on random arrival of parts production tasks, and adds the buffer occupancy as an evaluation index to realize machine on-off control on the basis of the above researches. However, there are often unstable operations in the actual production process, which includes the standby or off status of machine during the process due to the unreliability of the machine and the limited buffer capacity, and the above researches are all oriented to the production scenario under the ideal state of the production line.

Therefore, some scholars have begun to study how to reduce the energy consumption of the system by regulating the working probability of the machine while meeting the expected productivity. For example, Li et al. [9] proposed a comprehensive model reflecting the productivity and energy consumption of a two-machine production system, and reduced energy consumption by analyzing the optimal allocation scheme of productivity under different machine work probabilities; Yan et al.[10] proposed an optimality solution algorithm to analyze the impact of machine working probability on the energy consumption model of a minimized two-machine production system with production speed constraints; Yan et al. [11] proposed a heuristic energy-saving algorithm (ECS) to optimize the productivity of two-machine production line by establishing a polynomial optimization model for start-up, standby, and working energy of equipment. However, the above research is mainly oriented to the energy consumption during the operation of production system equipment, and has not yet fully considered the energy consumption of product storage, transportation, and apportionment during the production process.

The balance between energy efficiency and productivity is a systemic issue, which requires not only the thoroughness of energy consumption modeling, but also the thoroughness of the research perspective. Existing research is mainly focused on the on-off control strategies for efficient service of production lines producing known products, when the line produces unknown products in the future, the studied on-off strategy will be difficult to apply. Therefore, how to research from the perspective of efficient design and development of production lines to cope with the ever-changing product energy efficiency research in the future production line processing is an issue that needs to be addressed urgently.

In order to response to the above shortcomings and needs, we propose a new concept of inherent energy efficiency of the production system which considers the unreliability of

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machines and the limited capacity of the buffer zone based on the previous research on the inherent energy efficiency of machine tools and analyzed its characteristics. Secondly, taking the two-machine Bernoulli serial lines as an example, a specific energy efficiency model was established. Then combined with the correlation between machine tools in the production system, the impact of different buffer capacities and machine working probabilities on the productivity and energy consumption of two-machine Bernoulli serial lines was discussed. Finally, a numerical simulation was performed to verify the effectiveness of the model and analysis methods proposed in this article.

II. Model Formulation

A. Inherent energy efficiency of production system

The concept of inherent energy efficiency forms the concept of energy efficiency with operational energy efficiency, and it aims to describe the inherent energy consumption characteristics and energy efficiency potential of different energy users, which was born in the design and creation stage of the energy-consuming subject, and acts on the whole life cycle service stage of the energy-consuming subject. Current research on inherent energy efficiency mainly focuses on machine tool level, for example, Liu et al. [12-13] proposed an inherent energy efficiency evaluation method based on virtual workpieces, and proposed the key performance indicators for assessing inherent energy performance. Liu et al.[14] proposed a novel method for obtaining the inherent energy efficiency factors of machine tool spindles to support the development of energy-efficient machine tools. In summary, current research on inherent energy efficiency on the equipment has been in-depth research.

However, when faced with the development and design of energy-efficient production systems and energy-saving transformation work, the above research on the inherent energy efficiency of the equipment layer is far from enough, how to ensure the needs of the development of energy-efficient production systems while considering the production performance parameters to meet the desired standard is a complex, systematic scientific problem.

Take the production line as an example, from the actual production process of the production line, the equipment will comes into a longer standby or downtime due to departmental coordination, personnel changes, routine maintenance, the rest of the equipment failure and other factors; In addition, the upstream and downstream equipment of the production line will be starved and blocked due to the limited capacity of the production line buffer, the above scenarios are difficult to solve because of operational energy efficiency, and the research perspective of inherent energy efficiency is urgently needed to make up for the shortcomings of this part of the research, so the inherent energy efficiency of the production system must take into account the possible situations of the production line of all the processes and changes in the production line in order to cope with the uncertainty of the production of the additional energy consumption, which has the following meanings:

1) Production system inherent energy efficiency refers to the comprehensive consideration of the production system's own operation of the energy consumption characteristics as well as the operation of the process stage of the ever-changing processing conditions and put forward to describe the production system's own energy consumption and energy efficiency characteristics of the concept, which was born in the design and upgrading stage of the formation of the production system, and play a role in the production system's entire life cycle.

2) The inherent energy efficiency of a production system is not a simple addition of the inherent energy efficiency of each energy-using device, but a research method that takes into account the correlation between each device and the inherent attributes of the production line itself, such as the production factors, and expresses all of the energy use of the production system through mathematical theory.

B. Description of two-machine Bernoulli serial lines

Based on the above characteristics of the inherent energy efficiency of the production system, this paper takes the two-machine serial lines as the basic research object. The system is composed of two machines and a buffer, as shown in Figure 1, (where the circle represents the machine and the rectangle represents the buffer.)

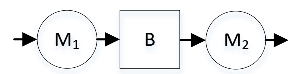

Figure 1. Two-machine Bernoulli Serial Line

We make the following assumptions and conventions about the system, which involves machines, buffers, and the interactions between them:

i. Classify the time axis in terms of cycles of the workpieces processed by two-machine production system and assume that the probability of machines m_1 and m_2 work in each time period is p_1 and p_2.

ii. The buffer B has a finite capacity N and it changes at the end of a cycle.

iii. The change in machine status is determined at the beginning of each period, while the status of the buffer is determined at the end of each period.

iv. If machine M_1 can process a part but the buffer B is full and machine M_2 cannot retrieve parts from buffer B, then machine M_1 is blocked. If machine M_2 can process a part but the buffer is empty and machine M_2 cannot retrieve parts from buffer B, then machine M_2 is starved.

v. The operation probabilities of all machines are independent of each other.

vi. Machine M_1 will never starve due to upstream production line issues, and machine M_2 will never be blocked due to downstream production line reasons.

In this article, by studying the changes in machine work probability and buffer capacity, we discuss the balance optimization problem between production line productivity and energy consumption based on the above constraints and assumptions, so as to minimize the energy consumed by the machine in a production cycle while maintaining productivity at no less than the required productivity.

TABLE I. THE MEANING OF THE PARAMETERS

Parameters	Meaning	Parameters	Meaning
P_{mi}^D	Standby power of the ith device	t_{mi}^D	Standby time of the ith device
E_{mi}	Energy consumption for the process	E_s	Energy consumption for the storage
E_T	Energy consumption for the transportation	E_F	Assessed energy consumption of the production
P_d	Effective output shared power	ω_i or ω_i'	Inherent energy efficiency factor for ith machine
p' and p''	Lower /upper bound probability to satisfy the productivity	p_i	Probability that the ith device will work
BL_1	Probability that the first device is blocked	ST_2	Probability that the second device is starved
WIP	Average work-in-process inventory in the buffer zone	PR	Productivity of production line

C. Modeling of inherent energy efficiency of two-machine Bernoulli serial production lines

The constant and decision variables that needs to be displayed in this article are shown in table 1. It is worth noting that the inherent energy efficiency coefficients ω_i and ω_i' can vary depending on the equipment itself, the exact meaning is explained by [15] as C_1 and C_2 .

Through the definition of inherent energy efficiency, the energy consumption model of the whole process per unit effective output can be expressed as:

$$E_{mi} = \omega_i p_i + \omega_i' \tag{1}$$

In a two-machine serial line, the energy consumption of processing unit products can be expressed as:

$$E = E_{m1} + E_{m2} + E_T + E_s + E_F \tag{2}$$

In the actual production process, the energy consumption of the two-machine serial line in different states can be divided into the following three situations:

(1) When m_1 is working, but buffer is full and m_2 can not get products from the buffer temporarily, which leads to the block of m_1. In this case, the specific energy model of unit output is:

$$E_{BL1} = BL_1\left[E + P_{m1}^D t_{m1}^D + P_d t_{m1}^D\right] \tag{3}$$

(2) When m_2 is working, but buffer is empty and m_1 can not produce products to the buffer temporarily, which leads to the starve of m_2. In this case, the specific energy model of unit output is:

$$E_{ST2} = ST_2\left[E + P_{m2}^D t_{m2}^D + P_d t_{m2}^D\right] \tag{4}$$

(3) When the buffer capacity is normal and m_1 and m_2 are all working, In this case, the specific energy model of unit output is:

$$E_m = \left(1 - BL_1 - ST_2\right)E \tag{5}$$

Therefore, combining the energy consumption of all the above processing conditions, we can get the inherent energy efficiency model of the two-machine Bernoulli serial production line as follows:

$$E_{line} = BL_1(P_{m1}^D t_{m1}^D + P_d t_{m1}^D) + ST_2(P_{m2}^D t_{m2}^D + P_d t_{m2}^D) + E \tag{6}$$

In order to simplify the formula, we substituted some parameters as follows:

$$E_{line} = BL_1 \times k_1 + ST_2 \times k_2 + E \tag{7}$$

III. MODELLING ANALYSIS

A. Energy efficiency analysis of two-machine Bernoulli serial line with the same working probability

In this section, we can suppose that $p_1 = p_2 = p$ and express the parameter according to the previous research[16], and energy efficiency in this case can be expressed as follows:

$$\begin{aligned} Min: E_{line} = &\left(k_1 + k_2\right)\frac{p(1-p)}{N+1-p} + P_d\frac{(N+1)}{2p} \\ &+ \left(\omega_1 p + \omega_2 p + \omega_1' + \omega'\right) + E_s + E_T \end{aligned} \tag{8}$$

Subject to :

$$PR \geq PR_d \tag{9}$$

$$0 < p < 1 \tag{10}$$

And the derivation of the theorem in this section requires the following lemma:

Lemma 1.

Under the assumptions and conventions (i)-(vi) and the expected productivity constraint formula (13), this problem has the following properties:

To make sure $PR \geq PR_d$, the optimal working probability of the machine should satisfy $p_E \geq p'$,where $p' = \frac{PR_d(N+1)}{N + PR_d}$

According to the above lemma, the conclusion of the theorem in this section can be obtained by the derivative method and is shown as follows:

Case 1: $N = 0$

Theorem 1.

When the production line machines have the same working probability and the buffer capacity is equal to 1, the minimum energy consumption to meet the desired productivity is:

(1) If $\sqrt{\frac{P_d}{2\left(k_1 + k_2 + \omega_1 + \omega_2\right)}} \geq 1$, the optimal working probability p_E is infinitely close to 1, and the minimal energy consumption is

$\left(k_1+k_2+\omega_1+\omega_2\right)+\frac{P_d}{2}+\omega_1'+\omega_2'+E_s+E_T$;

(2)If $0<\sqrt{\frac{P_d}{2\left(k_1+k_2+\omega_1+\omega_2\right)}}<1$, the optimal working probability p_E is $\sqrt{\frac{P_d}{2\left(k_1+k_2+\omega_1+\omega_2\right)}}$, and the minimal energy consumption is $\sqrt{2P_d\left(k_1+k_2+\omega_1+\omega_2\right)}+\omega_1'+\omega_2'+E_s+E_T$;

Case 2: $N \geq 0$

Theorem 2.

When the production line machines have the same working probability and the buffer capacity is larger than 0, the minimum energy consumption to meet the desired productivity is:

(1) If zero point of second derivative $\hat{p} \leq 0$, and $\frac{\partial E_{line-2}}{\partial p}(1) \geq 0$, or if zero point of second derivative $0<\hat{p}<1$, and $\frac{\partial E_{line}}{\partial p}(\hat{p}) > 0$, $\frac{\partial E_{line}}{\partial p}(1) \geq 0$, or if zero point of second derivative $\hat{p}>1$, the optimal working probability p_E is infinitely close to p' , and the minimal energy consumption is $\left(k_1+k_2\right)\frac{p'(1-p')}{1+N-p'}+\left(\omega_1+\omega_2\right)p'+P_d\frac{(1+N)}{p'}+\omega_1'+\omega_2'+E_s+E_T$;

(2) If zero point of second derivative $\hat{p} \leq 0$, and $\frac{\partial E_{line-2}}{\partial p}(1)<0$, here exists situations as follows from the zero point of derivative $\hat{\hat{p}}$:

1)when $1-\hat{\hat{p}} >\left|\hat{\hat{p}}-p'\right|$, or if zero point of second derivative $0<\hat{p}<1$, and $\frac{\partial E_{line}}{\partial p}(\hat{p}) \leq 0$, the optimal working probability p_E is infinitely close to 1, and the minimal energy consumption is $\omega_1+\omega_2+P_d\frac{(N+1)}{2}+\omega_1'+\omega_2'+E_s+E_T$;

2) when $1-\hat{\hat{p}} \leq \left|\hat{\hat{p}}-p'\right|$, the optimal working probability p_E is infinitely close to p' ,and the minimal energy consumption is Theorem 2. (1).

B. Energy efficiency analysis of two-machine Bernoulli serial line with the same working probability

In this section, we can suppose that $p_1 \neq p_2$ and according to the previous research [11] we can, and in order to minimize energy usage and achieve expected productivity, work probability constraints are proposed as $p_1 p_2 = p^*$.

The expression of energy efficiency in this case is expressed as follows:

$$\begin{aligned} E_{line\text{-}2} = {} & k_1\frac{p_1\left(p_1-p_2\right)}{p_1-p_2\alpha^N(p_2,p_1)}+k_2\frac{p_2\left(p_2-p_1\right)}{p_2-p_1\alpha^N(p_1,p_2)}+\omega_1 p_1 \\ & +\omega_2 p_2+P_d\frac{\left(1-p_1\right)\left(1-N\alpha^N(p_1,p_2)\right)}{p_2-p_1}+\omega_1'+\omega_2'+E_s+E_T \end{aligned} \tag{11}$$

Subject to :

$$p_1 p_2 = p^* \tag{12}$$

$$PR \geq PR_d = p_2\left[1-Q(p_1,p_2,N)\right] \tag{13}$$

And the derivation of the theorem in this section requires the following lemma:

Lemma 2.

Under the assumptions and conventions (i)-(vi) and the expected productivity constraint formula (13), this problem has the following properties:

To make sure $PR \geq PR_d$ and $p_1 p_2 = p^*$, p_1 need to be constrained to a range $[p_1', p'']$, which can be calculated by $PR_d = p_2\left[1-Q\left(p_1,\frac{p^*}{p_1},N\right)\right]$;

Case 1: $N=0$

Theorem 3.

(1) If $p_2 \geq p_1$, zero point of derivative $\hat{p}_1 \leq 0$, or if $p_2 < p_1$, zero point of derivative $0<\hat{\hat{p}}_1<1$,and $\left|\hat{\hat{p}}_1-p_1'\right| \geq \left|\hat{\hat{p}}_1-p_1''\right|$, the optimal working probability of m_1 equals to p' , the minimal energy consumption of production line is $k_1 p_1'+k_2\frac{p^*}{p_1'}+\omega_1 p_1'+\omega_2\frac{p^*}{p_1'}+P_d\frac{(1-p_1')}{\frac{p^*}{p_1'}-p_1'}+\omega_1'+\omega_2'+E_s+E_T$;

(2) If $p_2 \geq p_1$, zero point of derivative $0<\hat{p}_1<1$, the optimal working probability of m_1 equals to $\hat{p}_1$, the minimal energy consumption of production line refer to Theorem 3.(1).

(3) If $p_2 \geq p_1$, zero point of derivative $\hat{p}_1>1$, or if $p_2 < p_1$, zero point of derivative $\hat{\hat{p}}_1<0$, or if $p_2 < p_1$, zero point of derivative $0<\hat{\hat{p}}_1<1$,and $\left|\hat{\hat{p}}_1-p_1'\right|<\left|\hat{\hat{p}}_1-p_1''\right|$, the optimal working probability of m_1 equals to p'' , the minimal energy energy consumption of production line refer to Theorem 3.(1).

Case 2: $N=1$

Theorem 4.

(1) If zero point of derivative $\tilde{p}_1<0$, the optimal working probability of m_1 equals to p' , the minimal energy consumption of production line is $k_1\frac{p_1'\left(p_1'-\frac{p^*}{p_1'}\right)}{p_1'-\frac{p^*}{p_1'}\alpha(\frac{p^*}{p_1'},p_1')}+k_2\frac{\frac{p^*}{p_1'}\left(\frac{p^*}{p_1'}-p_1'\right)}{\frac{p^*}{p_1'}-p_1'\alpha(p_1',\frac{p^*}{p_1'})}+\omega_1 p_1'+\omega_2\frac{p^*}{p_1'}+\frac{P_d p_1'}{p^*}+\omega_1'+\omega_2'+E_s+E_T$;

(2) If zero point of derivative $0<\tilde{p}_1<1$, the optimal working probability of m_1 equals to $\tilde{p}_1$, the minimal energy consumption refer to Theorem 4.(1);

(3) If zero point of derivative $\tilde{p}_1>1$, the optimal working probability of m_1 equals to p'' , the minimal energy consumption refer to Theorem 4.(1).

In case 3, we simplified the formula and only analyzed its tendency, which is expressed as follows:

$$\begin{aligned} F = {} & \left[\frac{k_1}{k_2}\frac{p_1\left(p_1-p_2\right)}{p_1-p_2\alpha^N(p_2,p_1)}+\frac{p_2\left(p_2-p_1\right)}{p_2-p_1\alpha^N(p_1,p_2)}\right] \\ & +\left[\frac{\omega_1}{\omega_2}p_1+p_2\right]+P_d\frac{\left(1-p_1\right)\left(1-N\alpha^N(p_1,p_2)\right)}{p_2-p_1} \end{aligned} \tag{14}$$

Then we assigned values to various parameters and obtained the following trends based on the F-function, which is shown in figure 2:

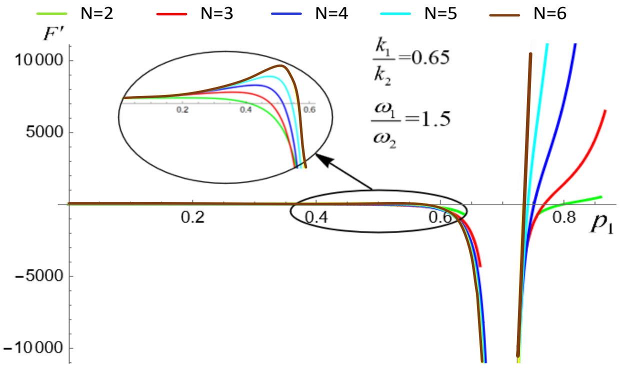

Figure 2. The derivative of the F-function against p

From the results, we can conclude that there always exists minimum energy consumption while ensuring the desired productivity when $p_1 < p_2$ and $p_1 > p_2$, and the fluctuation of energy consumption value rise and fall increases with the increase of buffer capacity N. Therefore, the setting of buffer capacity and the research related to buffer storage energy consumption are of great significance in the study of the minimum energy consumption of production system, which should not be neglected.

IV. Simulation Analysis

In this section, we categorize and assign specific values of the basic parameters of the inherent energy efficiency model in the above sections and carried out the simulation based on the above values through MATLAB software.

A. *Numerical definition of production lines*

In this subsection, we categorize the situation and assign specific values to the basic parameters of the Bernoulli two-machine serial production line inherent energy efficiency model in the above sections, as shown in Tables 2 and 3 below.

TABLE II. Basic Parameter Categories and Value Settings

Parameter categories 1	Parameter categories 2	Value settings
$\omega_1 = \omega_2$	/	1=1
		2=2
		3=3
$p_1 = p_2$	/	0.85=0.85
		0.9=0.9
		0.95=0.95
$\omega_1 \neq \omega_2$	$\omega_1 > \omega_2$	2 > 1
		3 > 1
		5 > 2
	$\omega_1 < \omega_2$	1 < 2
		1 < 3
		2 < 5
$p_1 \neq p_2$	$p_1 > p_2$	0.95 > 0.9
		0.9 > 0.85
		0.85 > 0.8
	$p_1 < p_2$	0.9 < 0.95
		0.85 < 0.9
		0.8 < 0.85

TABLE III. Numerical Simulation Analysis Program

Groups	Scenario 1	Scenario 2
$\omega_1 = \omega_2$, $p_1 = p_2$	$p_1 = p_2$	$\omega_1 = \omega_2 = 1$
	$p_1 = p_2$	$\omega_1 = \omega_2 = 2$
	$p_1 = p_2$	$\omega_1 = \omega_2 = 3$
$\omega_1 = \omega_2$, $p_1 \neq p_2$	$p_1 > p_2$	$\omega_1 = \omega_2 = 1$
	$p_1 < p_2$	
	$p_1 > p_2$	$\omega_1 = \omega_2 = 2$
	$p_1 < p_2$	
	$p_1 > p_2$	$\omega_1 = \omega_2 = 3$
	$p_1 < p_2$	
$\omega_1 \neq \omega_2$, $p_1 = p_2$	$p_1 = p_2$	$\omega_1 > \omega_2$
		$\omega_1 < \omega_2$
$\omega_1 \neq \omega_2$, $p_1 \neq p_2$	$p_1 < p_2$	$\omega_1 > \omega_2$
		$\omega_1 < \omega_2$
	$p_1 > p_2$	$\omega_1 < \omega_2$
		$\omega_1 > \omega_2$

B. *Analysis of simulation result*

We use MATLAB software to obtain the simulation results of inherent energy efficiency of different production parameters of the Bernoulli two-machine production line. The simulation results of all production lines show three kinds of energy consumption trends (i.e., some of the energy consumption trends are approximately the same, and the differences exist only in the y-axis size)

1) From figure 3, we can conclude that when the production parameters of lines are identical, the energy consumption of the production line is a monotonically increasing function of the buffer capacity, and its growth rate changes differently with the increase of the buffer capacity. The above conclusion fully illustrates that, when we set up the design or upgrade the production line with different energy consumption coefficients, the setting of the buffer capacity is of great significance, and we need to choose a more appropriate buffer capacity based on the specific characteristics of the production line equipment's inherent energy efficiency.

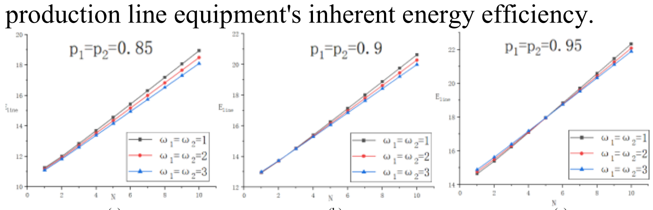

Figure 3. Relationship between buffer capacity and energy consumption when parameters are identical

2) From figure 4, we can conclude that when the production parameters of lines are partially identical, the trends of production energy consumption and buffer capacity are similar, and there exists an optimal energy consumption buffer capacity solution for all of them. In addition, the optimal buffer capacity solutions are different for production lines with different inherent energy efficiency coefficients.

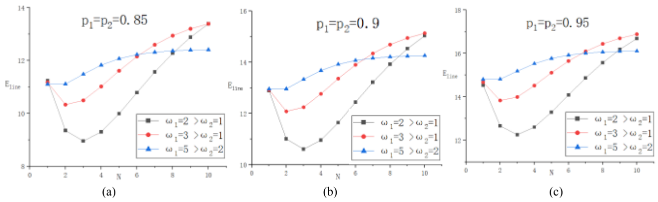

Figure 4. Relationship between buffer capacity and energy consumption when parameters are partially identical

3) From figure 5, we can conclude that when the production parameters of lines are entirely different, an increase in buffer capacity can alleviate the energy consumption of a production line due to blocking or starvation, but this alleviation is reduced when the buffer capacity is too large and can increase the cost of the buffer and its maintenance, which means we should set the buffer capacity infinitely close to 5 as much as possible to ensure the optimization of energy consumption.

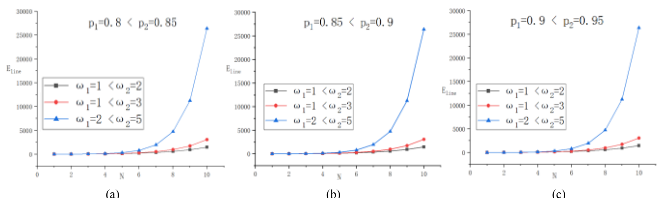

Figure 5. Relationship between buffer capacity and energy consumption when parameters are entirely different

In conclusion, the specific energy model established based on the inherent energy efficiency of two-machine Bernoulli serial production system in this paper can effectively provide theoretical guidance from the perspective of the inherent energy efficiency characteristics in the design of the production line with different production parameters or upgrading and remodeling.

V. Conclusion

In this paper, a specific energy efficiency model based on the inherent energy efficiency is established for the Bernoulli two-machine serial lines, and the apportioned energy consumption for the storage and transportation of the product in the buffer zone is also considered. In order to find the balance point between the optimal energy consumption of the production system and the buffer capacity by using this model, this paper has done the following works: firstly, the formulaic problem expression of the model is specifically characterized for the case of different buffer finite capacities; secondly, the impact of machine unreliability on the production system's energy consumption under the case of buffer capacity determination with the same and different working probability of machines is analyzed. Finally, multiple serial production lines are simulated through numerical analysis based on the energy efficiency model, and the inherent energy efficiency model and analysis method are used to provide theoretical guidance for the formation of multiple energy-efficient production lines, which improve the energy efficiency of the production system while meeting the desired productivity.

In future research work, our study will move from Bernoulli two-machine serial production systems to three-machine and multi-machine serial production systems, or production lines with other unreliability models.

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