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Cheng-Lin Liu
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Yan Wang
School of IOT Engineering
Jiangnan University
Wuxi, Jiangsu, China

Cheng-Lin Liu
School of IOT Engineering
Jiangnan University
Wuxi, Jiangsu, China

Zhi-Cheng Ji
School of IOT Engineering
Jiangnan University
Wuxi, Jiangsu, China

ISBN 978-981-15-4461-3 ISBN 978-981-15-4462-0 (eBook)
https://doi.org/10.1007/978-981-15-4462-0

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Preface

Recently, the problems of energy consumption and carbon emission in manufacturing have received global attention. Although the energy consumption problem in the process industry has attached much attention, it is also very prominent in the discrete manufacturing industry. To our knowledge, the effective energy consumption of the equipment is less than 30% in the discrete production line. Over 70% energy consumption costs on standby, no-load, unreasonable process parameters and routes. Hence, the research on quantitative analysis and optimal control of energy efficiency in discrete manufacturing system is a meaningful work. Most of the current relative works are focused on the analysis of the relationship between equipment energy consumption and process parameters. This is a local optimization perspective without considering the global optimization of the overall production line energy consumption.

Therefore, this book proposes some energy efficiency quantitative analysis and optimal methods for the discrete manufacturing system from the view of global optimization. To analyse and optimize the energy efficiency for discrete manufacturing systems, this book uses the real-time acquisition of energy consumption data, models the energy consumption, constructs the energy efficiency quantitative indices system and proposes a principal component quantitative analysis and a combined energy efficiency quantitative analysis based on rough set and AHP. Then, an energy quantitative analysis application system is built based on the presented analysis methods. Furthermore, this book designs several optimal control strategies including a static energy efficiency optimization based on knowledge and MOPSO, a high-dimensional dynamic energy efficiency optimization, and a process parameter optimization decision. At the last of this book, an energy efficiency optimization control software system is designed. This book is valuable for postgraduate students, teachers, engineers and individual researchers in the field of discrete manufacturing systems.

Chapter 2 focuses on the deployment method of the discrete manufacturing system's energy consumption information acquisition network. In Chap. 3, a multi-source and multi-level integrated energy consumption model and an intelligent identification method of key parameters are proposed. Chapter 4 investigates a multi-layered energy efficiency quantitative analysis index system. Chapter 5 focuses on the quantitative analysis of energy efficiency based on rough set theory and AHM. Chapter 6 is concerned with the bottleneck identification methods of the discrete manufacturing system's energy consumption. Chapter 7 proposes a discrete energy consumption analysis method based on the improved principal component analysis. In Chap. 8, a static optimization and scheduling algorithm based on knowledge and MOPSO is presented to minimize the energy consumption, machine workload and completion time. Chapter 9 studies the problem of production/energy consumption high-dimensional multi-objective dynamic optimization. A pre-response dynamic scheduling mechanism and NSGA-III-based optimization algorithm are designed to address the unexpected work events. In Chap. 10, a process parameter optimization decision model and RWA-MOPSO solution algorithm are presented to minimize the energy consumption in discrete manufacturing system. On the basis of the methods presented in the previous chapters, Chap. 11 illustrates the development steps, environments, tools and functional modules of a real energy efficiency optimization software system. Also, some industrial applications are shown to validate the effectiveness of our methods and software.

Wuxi, China
September 2019

Yan Wang
Cheng-Lin Liu
Zhi-Cheng Ji

Contents

Notations

E_{c}	Cutting energy consumption
E_{m}	Motor energy consumption
E_{k}	Drive link kinetic energy
E_{f}	Friction loss
E_{a}	Load loss
ΔE	Frequency conversion loss
E_{e}	Energy consumption of electrical control system
E_{as}	Energy consumption of each auxiliary system
$\eta(t)$	Instantaneous energy efficiency
$P_{\mathrm{o}}(t)$	The effective energy change rate of the manufacturing system at a certain time t
$P_{\mathrm{in}}(t)$	The input energy change rate
E_{p}	Energy efficiency of a process
E_{o}	Effective energy of a certain process or a certain period of time
E_{in}	Energy consumption of manufacturing system
η_{sec}	Energy efficiency under specific energy consumption
E_{ms}	Energy consumption of a manufacturing system
O_{E}	Effective output of a manufacturing system
E_{output}	Output energy
E_{input}	Input energy
η_{ee}	Machine energy efficiency
E_{mt}	Total energy consumption of a machine tool
$P_{\mathrm{c}}(t)$	Machine tool's cutting power
$P(t)$	Total machine processing power
P_{rfo}	Fixed power attenuation during the machine tool's normal operation
$P_{\mathrm{sp}}(t)$	Input power of the main transmission system
T_{s}	Start time of the manufacturing process
T_{e}	End time of the manufacturing process

$P_{\mathrm{u}}(t)$	Idle power of the machine tool
$P_{\mathrm{ad}}(t)$	Additional load loss of the machine tool
a_0	Additional load loss factor
a_1	Additional load loss factor
$\hat{P}_{\mathrm{c}}(t)$	Predictive cutting power of the machine tool
$\mathrm{E}\{\cdot\}$	The mean value
$\boldsymbol{\theta}$	The parameter
$\mathbf{h}(k)$	Observable data vector
$J(\boldsymbol{\theta})$	$\boldsymbol{\theta}$ criterion function
$\hat{\boldsymbol{\theta}}$	Least square estimate of parameter $\boldsymbol{\theta}$
$u(k)$	Input variables of system
$z(k)$	Output variables of system
$n(k)$	Noise variables of system
$A(z^{-1})$	Multinomials of the retardation factor z^{-1}
$B(z^{-1})$	Multinomials of the retardation factor z^{-1}
z^{-1}	Retardation factor
L	Data length
$\hat{\boldsymbol{\theta}}(k)$	Estimate value of $\boldsymbol{\theta}(k)$
$\mathbf{I}$	The unit matrix
$\mathbf{K}(k)$	The gain matrix
$\mathbf{P}(k)$	The covariance matrix
$\Gamma(k, i)$	The discount factor
$\Lambda(i)$	The weighting factor
$\mu(j)$	The forgetting factor
β	The sufficiently large positive integer
$\boldsymbol{\varepsilon}$	The sufficiently small real vector
P_{dec}	The total load irrelevant energy consumption
C_i	The power of a certain auxiliary energy consumption sub-system, which is normally a constant
g_i	A certain energy consumption sub-system is being used: 1 stands for yes, and 0 stands for no
P_{in}	Input power
P_{a}	Inverter forward loss
P_{b}	Inverter switch loss
P_{c}	Inverter recovery loss
P_{Fel}	The motor stator's iron loss
P_{f}	The friction loss
P_{w}	The wind loss
P_{cu1}	The motor stator's copper loss
P_{cu2}	The motor rotor's copper loss
P_{st}	Stray loss
P_{s}	The mechanical transmission system's energy consumption

P_{m}	The transmission system's friction loss
P_{z}	The transmission system's damping loss
P_{const}	Fixed loss
P_{var}	Variable loss
P_{imotor}	The motor's input power
P_{cu}	Copper loss
P_{Fe}	Core loss
P_{mec}	Mechanical loss
P_{ad}	Stray loss
P_{out}	Mechanical output power
ω_{m}	The angular speed
T_{en}	The electromagnetic torque
R_a	The stator resistance
B_{m}	The motor's damping coefficient
K_{T}	The motor's torque coefficient
K_{g}	The coupling's transmission ratio
B_{ls}	The ball screw's damping coefficient
μ_{v}	The viscous friction coefficient
μ_{c}	The Coulomb friction coefficient
η_{bse}	The ball screw drive efficiency
P_{pitch}	The ball screw's pitch
F_{ext}	The horizontal weight of the cutting force
M_{weight}	The machine tool's weight
i	The task number
k	The procedure number
j	The step number in the procedure
θ_l	Process parameters
O_n	The process route
M_{ik}	Processing equipment of k procedure of task i
$E_{u,M_{ik}}$	The facility's idle energy consumption
P_{idk}	The idle power of equipment no. k
z_{ik}	The total number of the facility's processing tasks
s_{ik}	The batch volume
t_{cik}	The processing time of task no. i at the machine tool no. k
t_{uik}	The idle time of the machine tool no. k
F_p,F_q	The two neighbouring structural features of the same processing part
$E_{\mathrm{non}}^{(F_p,F_q)}$	The idle energy consumption from the processing of feature p to the start of processing the next q
$E_{\mathrm{tp}}^{(F_p,F_q)}$	The idle cutting energy consumption from machining of feature F_p to machining of the next F_q
$E_{\mathrm{tc}}^{(F_p,F_q)}$	Automatic cutter changing energy consumption from machining of feature F_p to machining of the next F_q

n	Spindle speed
x, y, z	Tool coordinate
I_{spindle}	Spindle current
U_{spindle}	Spindle voltage
f	Feed rate
U_{in}	Input voltage
I_{in}	Input current
P_{stdby}	Standby power
P_{idle}	Idle power
V	The space volume of this basic hypercube
V_t	The volume of the space surrounded by this sample
n_{cmp}	The case number of the category i
$v_{d_{ij}}$	The decisional attribution i energy consumption of case no. j in the category i
$\overline{v_{d_i}}$	The average energy consumption of category i
n_{cond}	The case number of the category i
$v_{d_{ij}}$	The decisional attribution i energy consumption of case no. j in the category i
n_{num}	The number of processing parameters
Δx_j	Δx_j represents the difference after the processing parameters are normalized
α_j	The deviation after the standardization of the processing parameters
n_{obj}	The number of the selected features
β_i	The weighting factor after normalizing the attributes' importance of various features
$\lambda_{\max}$	The largest feature value
C_1	Energy consumption per ten thousand yuan production
S_1	The total amount of energy consumption
M_1	The industry added value
C_2	Energy consumption per ten thousand yuan added value
S_2	The total added value of the energy consumption
M_2	The industrial added value
C_3	Comprehensive energy consumption per unit product
N	The production output
C_4	Amount of energy saving per unit product
C_3'	The total amount of energy consumption per unit product after the energy saving optimization
C_5	The product energy utilization level
C_0	The comprehensive energy consumption per unit among the advanced-level products in China
C_6	Processing facility's energy efficiency
S_3	The total amount of energy consumption when the processing facility is cutting

S_4	The total amount of energy consumption of the processing facility throughout the entire production process
C_7	Energy transmission efficiency
S_5	The total amount after the energy has been transmitted
S_6	The total energy input amount
C_8	Energy conversion processing efficiency
S_7	The total amount of energy processing and conversion output
S_8	The total amount of energy processing and energy input
C_9	Processing technique energy efficiency
C_{10}	The comprehensive energy consumption per unit product's entire production cycle
S_9	The total amount of the energy consumption per unit product's technological process
C_{11}	Production resources scheduling energy efficiency
C_{12}	The total amount of energy consumption per unit product prior to the production resources scheduling
$C_{12}^{'}$	The total amount of energy consumption per unit product after the application of the production resources scheduling scheme
S	The decision table
D	The decision attribute set
C	The conditional attribute set
U	Object collection
V	Attribute value set
F	An information function
$\mathrm{Sig}(c)$	The weight significance of condition attribute Cin the decision table
$W_{Ai}(\mathrm{c})$	The weight of condition attributes (indexes) C
w_j	The combinational weight the item j sub-index relative to the total index
w_i	The combinational weight of the item i sub-index
w_{ij}	The weight of item j sub-index relative to i sub-index
w_{Ai}	Objective weight value
w_{Bi}	Subjective weight value
ς	The number of decision index
ξ	The number of alternative options
$r_{i,m}$	The degree of membership of u_i to c_j
c_k^i	The original value of item k sub-index in the number i option
c_k^*	The best value of the item k sub-index
W	The weight matrix
R	The quantitative analysis matrix
j_i	Quantitative analysis index for a single index c_i

$\mathrm{TOW}_{\min}$	Minimum difference between poles
$\mathrm{TOW}_{\max}$	Maximum difference between poles
L_i^k	Grey relational coefficiency
C^*	The optimal index set
A_i	The node degree
a_{ij}	Whether node i and node j are connected
B_r	The betweenness of node r
λ_{st}	The number of all the shortest routes between node s and node t
$\lambda_{st}(r)$	The number of all shortest routes between node s and node t which pass node r
e_{st}	The reciprocal of the distance between node s and node t
d_{st}	Represents the number of the edges which pass through node s and node t
W_{st}	The route energy consumption between node s and node t within a given period
N_{kind}	The kinds of components
a_{sti}	Whether there is the component mobilization of the component i between node s and node t
P_{sti}	The different transportation equipment power equipped for component mobilization
T_{sti}	The operation time of the transportation equipment for transporting i between node s and node t
C_r	The energy consumed by the equipment node r in a given period. u_i refers to the number of component i
H_i	The number of procedures of component i
β_{ijr}	The equipment coefficient
T_{ijr}	The cutting time of component i at procedure no. j
T'_{ijr}	Idle time of component i at procedure no. j
P_{ncut}	The cutting power of equipment node r
P'_{nidle}	Idle power of equipment node r
α_1	The weight functions of route energy consumption
α_2	The weight functions of node energy consumption
U_{Ci}	The substance–relation–substance set contained within node C
$U(C_i, C_j)$	The intersection of the two indexes' corresponding sets
p	The index volume of the index system
W_j	The importance weight function value endowed to each index in the index system through the expert method's subjective empowerment
X_{ij}	The energy consumption evaluation index variable value of sample no. i, section j
$\mathrm{k}_{\mathrm{principal}}$	The number of principal components

F	The comprehensive result of the discrete manufacturing system's energy consumption sample
m	The number of processing equipment
N	The number of workpieces to be processed
c_{ijegk}	i, e represents the workpiece number, j, g represents the procedure number
h	The device number
M	The device set
J	The workpiece set
s	The largest procedure number of all workpieces
O_{ij}	Procedure j of workpiece J_i
M_{ij}	Procedure j of workpiece J_i the available device set of procedure O_{ij} for workpiece J_i
P_{ijk}	A certain procedure of the workpiece can be processed at multiple devices
R_c	Two workpieces can be processed at one device
t_{ijk}	The processing time of procedure O_{ij} at device M_k
S_{ijk}	The start time for processing procedure O_{ij} at device M_k
E_{ijk}	The finish time for processing procedure O_{ij} at device M_k
w_k	The energy consumption of a certain procedure of a certain workpiece at device M_k
E_i	The total energy consumption of all workpieces at device M_i
$E_{\text{total-ec}}$	The total energy consumption for processing all workpieces
ω_i	Weight value of no. i component
p_{itarget}	i component's target value at the best level
$\bar{p}_i$	The historical value of no. i component's priority level
C_M	The order completion time uses the device's minimalized maximum completion time
$E_{\min-\text{total}}$	Minimalized total production energy consumption
W_T	Minimalized machine's total load
W_M	Critical machine load
G	The target component set
H	Component set of historical scheduling
$\sum t_{ij}$	The length of time to complete producing this type of component
t_{day}	The number of days prior to the completion date
t_{work}	The daily working hours
$P_i(t)$	The priority level of component no. i
$imp\%$	The MOPSO algorithm's performance upgrade rate
t_0	Initial moment
t_l	Rescheduling time point $l = 1,\ 2,\cdots$

$n(t_l)$	Rescheduling time point t_l number of workpieces with machinable operations
$J_i(t_l)$	The i of the t_l moment contains the workpieces of the machinable process
$m(t_l)$	Number of machines that can be released at t_l time
$M_k(t_l)$	k machine released at t_l time, $k = 1, 2, \cdots, m(t_l)$
$C_i(t_l)$	t_l time, the completion time of all processable parts of the workpiece $J_i(t_l)$
$e_i^{\prime}(t_l)$	Number of machinable processes included in workpiece $J_i(t_l)$ at t_l time
$DD_i(t_l)$	t_l time, the delivery date of all processable parts of $J_i(t_l)$
$S_i(t_l)$	t_l time, workpiece $J_i(t_l)$ the start time of the first process in the process
$n * (t_l)$	Rescheduling time point t_l has the number of workpieces that can be processed and processed
p^{k_r}	t_l time, the remaining processing time of the processing process on $M_k\,(t_l)$
$I_i(t_l)$	t_l time, workpiece $J_i(t_l)$ subscript of the first process in all processable processes
$c_{i(I_i(t_l)-1)}$	Process $J_i(t_l)$, the completion time of the last process in the process that was completed before the t_l time
$O_{ij}(t_l)$	Step j in the workpiece $J_i(t_l)$, $j = I_i(t_l), I_i(t_l) + 1, \cdots, I_i(t_l) + e_i^{\prime}(t_l) - 1, r = 1$
$M_{ij}(t_l)$	Process $O_{ij}(t_l)$ is a collection of machinable machines at t_l
$p_{ijk}(t_l)$	Process $O_{ij}(t_l)$ processing time on the machine $M_k(t_l) \in M_{ij}(t_l)$, $k = 1, 2, \cdots, \left\|M_{ij}(t_l)\right\|$, $\|\bullet\|$ indicates the size of the collection
$s_{ij}(t_l)$	Start processing time of process $O_{ij}(t_l)$
$c_{ij}(t_l)$	The completion time of the last process of the machine $M_k(t_l)$ completed before t_l
$c^{k\_last}(t_{l-1})$	The completion time of the last process of the machine $M_k(t_l)$ completed before t_l
$n_{M_k}(t_l)$	Number of operations assigned to the machine $M_k(t_l)$ at t_l, $k = 1, 2, \cdots, m(t_l)$
$O^{r,M_k(t_l)}$	The r process assigned on the machine $M_k(t_l)$, $r = 1, 2, \cdots, n_{M_k(t_l)}$
$p^{r,M_k(t_l)}$	Process $O^{r,M_k(t_l)}$ processing time
$c^{r,M_k(t_l)}$	Finishing time of process $O^{r,M_k(t_l)}$
K_i^*	The delivery period elastic coefficient of the workpiece $J_i(t_l)$, which satisfies the positive distribution of 1.5 with a variance of 0.5
E_k	Machine M_k processing energy per unit time

$A_k(t_l)$	Machine $M_k(t_l)$ in rescheduling period t_l initial release time
$X_{ijk}(t)$	Binary variable
E_{total}	Total energy consumption
E_{st}	Energy consumption when machine starts
E_{s-s}	Machine standby power consumption
E_{ie}	Energy consumption when machine is no-load
$E_{i\text{c}}$	Cutting energy consumption during processing
t_c	Process time
v_c	Cutting speed
f_{afeed}	The amount of feed
a_{sp}	Cutting depth
$C_{FC}, x_{FC}, y_{FC}, n_{FC}, K_{FC}$	Coefficients related to part material and tool material
t_{ot}	Auxiliary time such as clamping
L_w	The length of the machined part
T	The life of the tool used for machining
t_{ct}	The time taken by the magazine to change the tool once
Δ	The margin left in the process
d_0	The diameter of the machined part
n	The spindle speed of the machine
C_T	Constant values related to machining conditions such as parts, tools and machine tools
$x_{\text{life}}, y_{\text{life}}, z_{\text{life}}$	The life factor of the tool
$n_{\min}$	The minimum values of the spindle speed of the processing equipment
$n_{\max}$	The maximum values of the spindle speed of the processing equipment
$f_{\min}$	The minimum values of the feed allowed by the processing equipment
$f_{\max}$	The maximum values of the feed allowed by the processing equipment
$F_{\max}$	Maximum cutting force
C_F, x, y, n, K_F	The coefficient associated with the machined workpiece and the cutting conditions
r_ε	Tool radius
$R_{\max}$	The maximum value required for the surface roughness of the part
η_{total}	The total efficiency of the machine tool
$P_{\max}$	The maximum cutting power indicated on the machine nameplate
F_c	Indicates the cutting force when the machine is machined
$P_{\text{population}}$	Population of n
D	Search space dimension

V_{id}	The speed of particle i in d-dimensional space
X_{id}	The position of particle i in the d-dimensional space
P_i	Individual extremum
P_g	Group extremum
$\omega(t)$	Inertia factor
$\omega_{\max}$	The maximum values of the inertia factor
$\omega_{\min}$	The minimum values of the inertia factor
d	Particle dimensions
i_{num}	The number of particles
t	The current number of iterations
i_{num}	The maximum number of iterations
$c_1 c_2$	Acceleration factor
x_i	The approximate minimum value obtained in $i - 1$ steps
u_i	A randomly generated unit vector
$P_{\text{optimization}}$	The optimal solution found by the particle swarm optimization algorithm
D_i	The crowded distance of the particles
$F(s)$	A collection of all particles with a non-dominated solution level of s
f_j^h	The hth objective function representing the jth particle, a total of p objective functions
l	The number of particles in $F(s)$set
$a_j^{\max}$	Maximum values of the corresponding j columns of the judgment matrix$A$
$a_j^{\min}$	Minimum values of the corresponding j columns of the judgment matrix$A$
p_{num}	The number of evaluation programs
q	The number of indicators

Chapter 1
Introduction

1.1 Discrete Manufacturing System

Discrete manufacturing system is an important support for the production of mechanical products and their parts, and its energy consumption is an important part of the carbon footprint of products [1]. Literatures [2, 3] show that the main energy-consuming machinery and equipments of discrete manufacturing system have large energy consumption and effective energy utilization rate of less than 30% on average. The energy-saving space is huge, and the carbon emissions caused by energy consumption are shocking. According to the literature [4], the global manufacturing industry produced nearly 50 billion tons of carbon emissions in 2001. It is expected that by 2030, global manufacturing carbon emissions will reach 100 billion tons, double the number in 2001. A set of data from MIT's research can visually illustrate the total energy consumption of a machine tool and the environmental emissions it brings [5]: a machine equipped with a corresponding auxiliary device, if the spindle power is 22 kW. The two-shift work system, in which the cutting time accounted for 57%, measured by the efficiency data of the US National Grid, the environmental emissions generated by the machine's electricity consumption for one year, and the fuel consumption is 20.7 mpg, driving 12,000 miles per year. Compared with SUVs, their CO_2 emissions are equivalent to the emissions of 61 SUVs.

Discretely manufactured products are often assembled from multiple parts through a series of discrete processes. The discrete manufacturing process is a complex process consisting of different parts processing sub-processes or parallel or series. Discrete manufacturing systems span different levels of products, workshops, tasks, manufacturing units and production equipment. Each level of energy consumption has its basic characteristics. Therefore, the discrete manufacturing system is much more complicated than the process manufacturing system. Complex characteristics such as variability in processing tasks, equipment and process diversity, complex tree characteristics of products and their manufacturing energy consumption, product energy consumption and dynamic characteristics of equipment (process) are often [6, 7]. The overall energy consumption, energy efficiency utilization and the

Y. Wang et al., *Quantitative Analysis and Optimal Control of Energy Efficiency in Discrete Manufacturing System*, https://doi.org/10.1007/978-981-15-4462-0_1

implementation of relevant at home and abroad green regulations, energy conservation and consumption reduction have become the first problem for the sustainable development of discrete manufacturing.

In recent years, China, the European Union, Japan, North America and other regions have launched plans to improve the energy efficiency of discrete manufacturing and carry out research on related mechanisms and technologies [8–10]. A large number of studies have shown that [11–16] the energy consumption of discrete manufacturing systems is closely related to equipment state and its motion properties, process parameters, process feature sequencing, product structure, production scheduling and start–stop control. In particular, for complex discrete manufacturing processes such as flexible manufacturing and mixed flow manufacturing, the energy consumption mechanism is complicated by the influence of process characteristics such as variable processing tasks, equipment state and process dynamics. The pre-unknownness of a large number of parameters in the processing parameter/thermodynamic energy consumption model, the highly nonlinear characteristics of the equipment energy consumption process and the inevitable randomness and dynamics in complex workflows pose challenges to the modelling, analysis and optimization of system energy consumption process. Therefore, the research on energy optimization of discrete manufacturing systems is of great scientific significance and engineering application value.

1.2 Energy-Related Factors and Characteristics

1.2.1 Energy-Consuming Components

The basic components of a typical discrete manufacturing system can be divided into four parts: production environment, production equipment, production objects and operators. The functional characteristics, usage status and utilization rate of these production factors will affect the energy consumption in manufacturing systems. The consumed energy in a production process can be divided into direct energy and indirect energy [17], where direct energy is the energy consumed by various processes (such as casting, processing, painting and inspection) for manufacturing products, and the indirect energy is the energy required to maintain the production environment in the workshop (such as lighting, heating and ventilation). Taking a typical machining manufacturing system of complex discrete manufacturing as an example, the mechanical manufacturing system is composed of nine types of processes such as cutting, pressure processing, casting, welding, special processing, heat treatment, covering, assembling and packaging. Energy-consuming components can be further divided into direct and indirect energy-consuming components according to their manifestations. Direct energy consumption from production machines depends on the operating state of the equipments. The process characteristics of the parts, the scheduling of the production system and the start–stop control strategy of the equipment constitute the indirect energy-consuming components.

1. **Direct energy consumption of machines**. The production equipment of discrete manufacturing systems is mostly CNC machine tools with machine–electric–liquid multi-source energy fusion characteristics. There are many energy-consuming components in a machine tool, including auxiliary system, main transmission system, feed system and other energy-consuming subsystems. It is a multi-component and multi-source energy-consuming system. The basic energy consumption characteristics of the motion unit are determined by its own structure and physical and motion properties [18], such as the structural design and motion control mode of each moving component. The energy consumption of each main component is shown in Table 1.1. During the operation of the production equipment, the energy loss caused by the interaction and mutual influence of the various moving parts makes the energy loss law quite complicated, and the energy consumption exhibits instantaneous dynamic changes in different operation stages such as starting, no-load and processing. The CNC machine tools mainly consume electric energy. The change of the whole machine power during the operation process depends not only on the performance of its internal component system, the movement composition of the components and the operating parameters, but also the processing object and the processing conditions.
2. **Production object process characteristics indirect energy consumption**. From the perspective of production objects, the same production equipment, different part materials, tool types and machining parameters will form different machining forces/torques, affecting the load of the moving unit of the processing equipment [19], thus consuming different energy.
3. **Auxiliary production equipment indirect energy consumption**. In addition to processing equipment, the energy consumption generated by other auxiliary processing equipment, such as lighting equipment, workshop handling equipment, workshop cooling and heating equipment.
4. **Production management indirect energy consumption**. In the process of processing, affected by the production planning scheduling and production resource scheduling scheme, the energy consumption difference of different batches of products during processing.

1.2.2 Energy Consumption Hierarchy and Characteristics

According to the different energy consumption levels of discrete manufacturing systems, the energy consumption of discrete manufacturing processes is analysed from three aspects: equipment layer, product layer and process layer:

Table 1.1 Function and energy consumption description of energy-consuming components in a CNC machine tool [18]

Name		Component composition	Functional description	Energy consumption statement
Processing power system	Spindle drive	Spindle motor and mechanical transmission components	Drive the tool or workpiece for high-speed rotation and provide cutting power	Cutting energy consumption $E_\mathbf{c}$ Motor energy consumption $E_\mathbf{m}$ Drive link kinetic energy $E_\mathbf{k}$ Friction loss $E_\mathbf{f}$ Load loss $E_\mathbf{a}$
	Feed drive	Feed shaft motor and mechanical transmission components	Electric tool or workpiece linear motion along the feed axis	
Electrical control system	Numerical control device	Computer machine display	CNC program processing and display	Frequency conversion loss ΔE Electrical control system energy consumption $E_\mathbf{e}$
	Spindle control	Spindle drive/inverter	Converting NC instruction of spindle into electrical signal	
	Feed axis control	Feed axis drive/inverter	Convert CNC commands of the feed axis to electrical signals	
Auxiliary system	Heat exhaling system	Fan	Electric control cabinet cooling	Energy consumption of each auxiliary system $E_\mathbf{as}$
	Cooling system	Cooling pump	Provide coolant	
	Chip removal system	Chip removal motor	Chip removal	
	Tool change system	Storage motor	Tool change	

1. Equipment layer energy consumption

Discrete workshop equipment layer has many types of energy consumption and large quantity. Workshop energy-consuming equipment contains trampolines, grinding machines, etc. Production and transportation energy-consuming equipment includes hanging towers, forklifts, etc., workshop production environment equipment such as refrigeration and air conditioning, heating and lighting. The energy consumption of each equipment in the discrete manufacturing workshop is mainly electric energy. As the main driving force of workshop processing equipment and auxiliary processing equipment, electric energy is an indispensable energy medium in the whole processing.

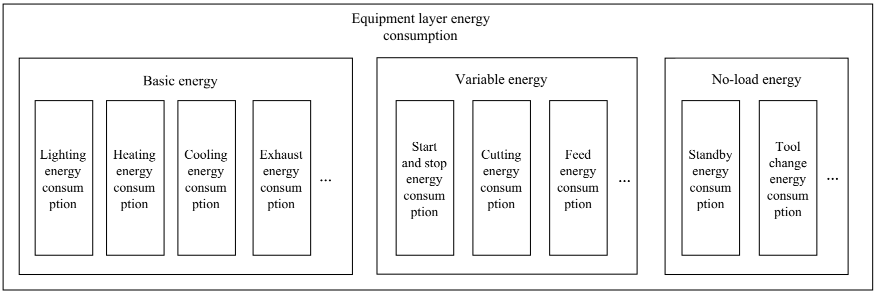

Fig. 1.1 Discrete manufacturing system equipment layer energy consumption

The energy consumption of the equipment layer is divided into three parts: basic energy, variable energy and no-load energy, as shown in Fig. 1.1. Basic energy includes energy consumption in system equipment such as lighting, hydraulics and cooling. Variable energy includes machine tool equipment start-up, cutting, tool change, feed and other processing energy consumption; during the machining process, the no-load energy generated by the machine tool standby due to the machining gap is no-load energy consumption, such as waiting for no-load, tool-less no-load energy consumption and no-load energy consumption during processing. Variable energy is the main body of the energy of the device layer. The greater the proportion of variable energy, the higher the energy efficiency of the device layer.

The operating state of machining equipment is divided into four categories: start-up, no-load between work steps, cutting and stop. When the equipment is switched between different states, the energy consumption also changes, as shown in Fig. 1.2. Among them, cutting energy consumption is the effective energy consumption part of the total energy consumption of machining equipment.

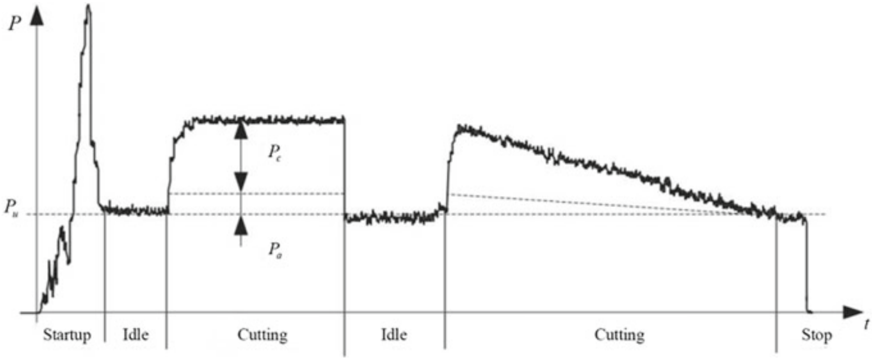

Fig. 1.2 Input power profile

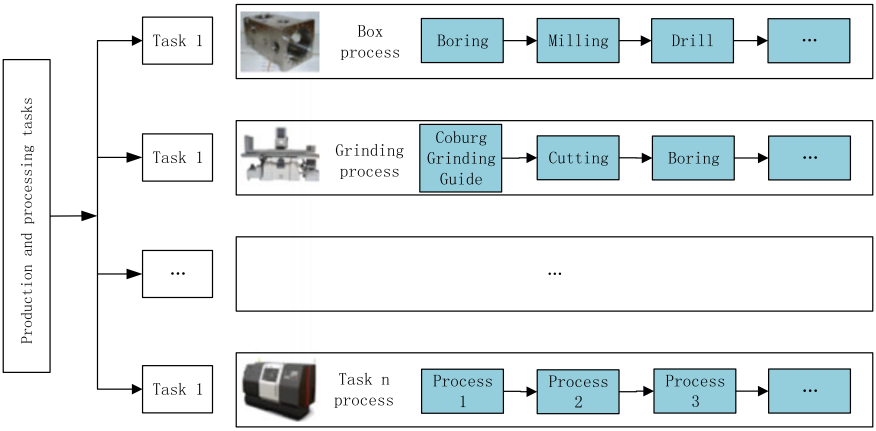

Fig. 1.3 Discrete manufacturing system task layer

2. Process layer energy consumption

Discrete manufacturing system processing technology has a variety of characteristics, the same product has a number of different processing routes, each process consists of several processing steps, the same process is processed on different equipment, and its energy consumption is generally different [20]. As shown in Fig. 1.3, the process layer contains all the processing routes of the product production process, which indirectly reflects the energy efficiency level of the equipment corresponding to all processed parts in the product processing process.

Considering the machining process of the workpiece, each machining task unit can be regarded as a machining process of a workpiece, and multiple machining operations are required to complete each machining task. Manufacturing system task layer energy consumption is determined by various factors such as process parameters, task plan and scheduling plan during production and processing. However, there are mainly two kinds of energy in the task layer of manufacturing system: First, the process energy consumption characteristics determined by factors such as processing parameters and process schedules, different process parameters and different process routes will bring about differences in energy consumption of processing equipment; second, the production planning and processing plan determine the energy consumption characteristics of the scheduling. Task-level energy consumption is defined as the energy consumption of the equipment required to complete a specific processing task for a discrete manufacturing system.

3. Product layer energy consumption

The discrete manufacturing system production process is the entire processing flow from raw material to product, including the processing of raw materials, transportation, product processing, assembly and rework [21], as shown in Fig. 1.4.