Int J Adv Manuf Technol
DOI 10.1007/s00170-015-7057-7

ORIGINAL ARTICLE

Energy consumption model and its simulation for manufacturing and remanufacturing systems

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Received: 6 November 2014 / Accepted: 18 March 2015

Abstract This paper adopts a method of researching the process of energy consumption in manufacturing/remanufacturing systems to achieve lean energy. This method can be used in typical machining systems, especially including the machining process of manufacturing and remanufacturing. To validate this approach, we model and simulate the system with the DEVS theory and input-output model. This model establishes the machining process of a product. On the basis of work station, which is used for receiving work pieces and energy, exporting products and information of different kinds of energy consumption. We can simulate manufacturing/remanufacturing of integration machining process and material flow, information flow, and energy flow of the coupling process. After that, classify the energy consumption according to the quality of the products. The solutions, which are the margin of error between simulation and measurement, show that this method is effective. The output results help manage energy resource and provide train of thought for saving energy and reducing consumption.

Keywords Manufacturing/remanufacturing systems · Energy consumption · DEVS · Input-output model

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1 Introduction

Dealing with the challenges of energy crisis, new energy resource is the fundamental way to solve the problem. However, energy conservation and achieving lean energy are also effective ways [1]. So, energy saving has become a strategic choice for China and the world in recent years. Energy analysis is a prerequisite for the implementation of energy conservation. On the basis of energy analysis, we can find some ways and excavate potential for energy conservation, to improve energy efficiency. A large number of researchers pay their attention to energy analysis of steel, oil, chemicals, cement, and other energy industries. Achieved remarkable results are provided to us. While in manufacturing systems (MS) based on machine tools, many researchers have done research related to energy conservation in different levels, which contain machine motors [2, 3], machine tools [4–8, 11], manufacturing systems [9, 10, 12–18], and so on.

Take a look on the following research about energy modeling analysis machining system. References [4–8] take the manufacturing system as the research object to establish model energy flow of manufacturing systems [4]; advance a content architecture framework of energy efficiency research on machining system [5]; focus on elector-mechanical main driving systems, auxiliary systems, and their comprehensive systems; and analyze their process of energy consumption [6–8]. Energy consumption forecasting and optimization for tool machines is provided [11].

Analysis of energy consumption on the enterprise level is meaningful, too. A framework for modeling energy consumption within manufacturing systems at plant and process levels is proposed, based on a product viewpoint. Some work about calculation of energy costs has been done [12, 13]. The enterprise energy consumption system has been modeled with the theory of Petri nets [14–17]. Some researchers propose a novel generic method to model the energy consumption behavior

Published online: 03 April 2015

of machines and plants based on a statistical discrete event formulation [18]. To estimate the energy consumption in the manufacturing process of a new product, a semantic model of energy consumption knowledge and its semantic representation are proposed [19]. A system of detecting energy consumption data and querying is developed, which is suitable for lager steel plant, scheme, and hardware [20].

The above literature used analyzing energy consumption of system in different ways properly—to strengthen manufacturing process, the energy consumption analysis, and simulation. However, they are not good at dealing with model's intuitive, logic, hierarchy, and scale at the same time. Different manufacturing units and correlation between different energy flow is not detailed consideration; the analysis of the overall system state changes also insufficiently in the processing of manufacturing process, at the same time, there is a lack of the study about energy consumption of classification.

The theory of Discrete Event System Specification (DEVS) has been used for dealing with the removal production line problem effectively [21]. On this basis, the theory of DEVS and input-output model is going to be used to model and simulate ordinary machining systems. In this paper, attention is focused on how to set up manufacturing/remanufacturing system of energy consumption model and to achieve its simulation. Which considers the changes in key variables of the system; the combining of the integration process of manufacturing and remanufacturing machining; the coupling of the flow of material, information, and energy; and the classification of energy consumption according to the quality of the products at the same time. This paper will proceed to deal with the above problems.

2 Manufacturing systems and DEVS

2.1 Characteristics of manufacturing systems energy consumption

Manufacturing systems has the characteristics of multi-level, multi-process complexity. A production line, a workshop, or a factory can be viewed as manufacturing systems at different levels. When manufacturing systems are running, the flow of material, information, and energy always move around. What is more, systems consist of different process, such as the process of manufacturing and remanufacturing.

The characteristics of manufacturing systems about energy dissipation are presented here.

- There are lots of facilities, including machine tools, auxiliary equipments, and so on.
- There are kinds of energy consumption, including electricity, natural gas, coal, and so on.
- The amounts of different energy, demand of different energy, depend on different facilities.
- The recovery of energy is decided by the ability of enterprises and the types of energy.

2.2 The architecture of the manufacturing/remanufacturing system

Due to the variability and complexity of manufacturing/remanufacturing system, in order to more clearly understand its architecture, it is important to be able to observe and understand from the angle of the system function. The system has the characteristics of modular structure; it can be divided into manufacturing process subsystem, resources subsystem, and environment assessment subsystem; and is a modular, hierarchical, and more coupling process of integration system.

According to the specifics of machining process, to establish a manufacturing/remanufacturing system of structure, see simulation diagram Fig. 1. It describes the whole simulation process of manufacturing system. As seen in Fig. 1, the manufacturing system consists of functions of different workstation (WS), transportation, and storage processes. The different functions of the WS are the core of the whole system. So, if we want to understand, analyze, and improve the manufacturing system's energy consumption, it is necessary to establish a system model for WS.

2.3 The concept of DEVS

The Discrete Event System Specification (DEVS) formalism provides a means of specifying a mathematical object called a system, developed by Zeigler to model and simulate discrete event dynamic systems in 1976 [22]. DEVS consist of atomic DEVS and coupled DEVS. An atomic DEVS is used to describe the behavior of atoms. A coupled DEVS is composed of multiple atomic and/or other coupled models, connected together through their input and output ports.

A classic atomic DEVS is a structure.

$$M = \{X, Y, S, \delta_{\text{int}}, \delta_{\text{ext}}, \lambda, \text{ta}\}$$

Where, X is the set of inputs. S is a set of states. Y is the set of outputs. $\delta_{\text{int}}: S \rightarrow S$ is the internal transition function. $\delta_{\text{ext}}: Q \times X \rightarrow S$ is the external transition function ($Q = \{(s,e) | s \in S, 0 \leq e \leq \text{ta}(s)\}$), e is the time elapsed since last transition, $\lambda: S \rightarrow Y$ is the output function. $\text{ta}: S \rightarrow R^+$ is the time advance function.

A classic coupled DEVS is a structure.

$$N = \left\{X, Y, D, \left\{M_{\text{d}} \middle| d \in D\right\}, \text{EIC, EOC, IC, Select}\right\}$$

Where X and Y define the sets of input and output events. M_{d} is a set of components of a coupled model, for each $d \in D$. EIC specifies the connections between external and component inputs, while EOC describes the connections between component and external outputs. IC defines the connections between

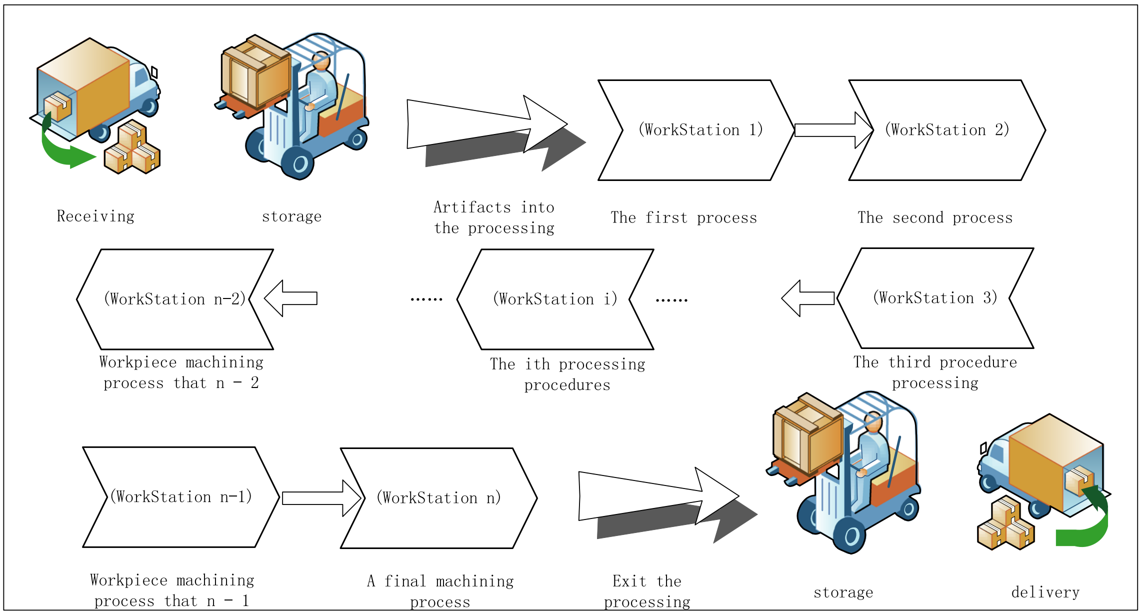


Fig. 1 Manufacturing/remanufacturing system structure simulation diagram

components themselves. Select is the tie-breaking function (used in classic DEVS but eliminated in parallel DEVS).

A basic Parallel DEVS is a structure.

$$\mathrm{PM} = \{X_{\mathrm{M}},\ Y_{\mathrm{M}},\ S,\ \delta_{\mathrm{ext}},\ \delta_{\mathrm{int}},\ \delta_{\mathrm{con}},\ \lambda,\ \mathrm{ta}\}$$

Where, the meaning of each variable is the same with classic atomic DEVS, except for δ_{con}. δ_{con}: $Q \times X \rightarrow S$ is the confluent transition function, which decides the next state in case of collision between external and internal events.

3 Model description

3.1 IDEF0 model of manufacturing systems

This paper discuss manufacturing systems from the perspective of the production line, which is based on a workshop and regard the production process as the main line, combining the flow of material, information, and energy (the flow of energy in the point). The model is presented in Fig. 2.

As a processing unit, workstation (WS) receives inputs (including materials, information, and energy, etc.) and sends out outputs (including products, semi-finished products, scrap, and etc.), which is controlled by external conditions (including technology, quality, etc.) and internal conditions (including organization, software, equipment, etc.). The links between WS can represent the continuous process of manufacturing/remanufacturing. The sash on the left is used for providing energy for WS. The sashes on the right are used for receiving left energy and different energy consumption information. The sash on the bottom represents products, including products, semi-finished products, scrap, and etc. (Fig. 2).

3.2 The behavior of WS

On the basis of IDEF0 model, WS is the basic unit of manufacturing systems. It is necessary to pay more attention to WS and build a general WS model. Before build WS model, the behavior of WS is presented in Fig. 3.

WS consists of three atomic models, which are upstream, machine and downstream model (more details in Section 3.3). WS receives work pieces and energy, then exports products, scrap, information of different kinds of energy consumption and etc. Upstream model is responsible for receiving, staging, and exporting different batches of work pieces from last WS to machine model. Machine model proceed with the batch one by one, consuming energy at the same time. Downstream model is responsible for receiving, staging, and exporting of products. Energy consumption will be classified according to the quality of the products.

According to Section 2.1, we know that manufacturing systems contains lots of facilities, which consume different kinds of energy. What is more, the amounts of different energy depend on different facilities. Input-output model proves to be a useful tool to solve above problems [23]. So, it's reasonable to analyze the process of energy consumption with DEVS and input-output model, and establish WS, upstream, machine, and downstream model, respectively.

3.3 Detailed atomic models

Before introducing DEVS model of WS, this section describes the behavior of atomic models firstly. Then, we will focus on the DEVS atomic model of machine and its behavior; among them, upstream and machine models are defined by a classic

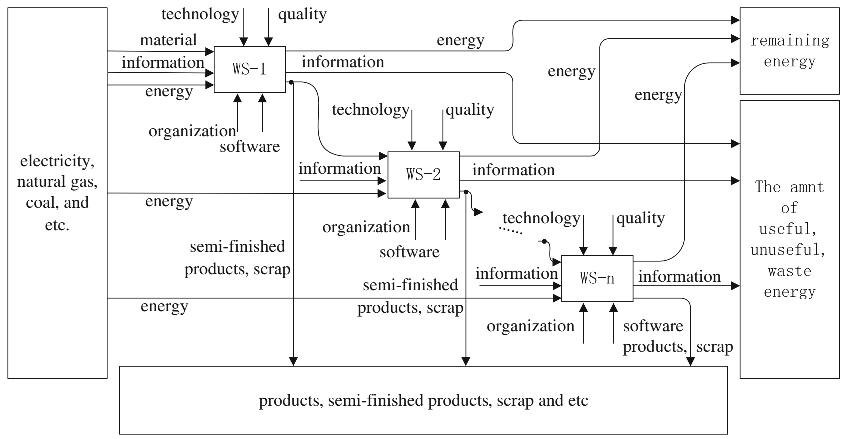


Fig. 2 IDEF0 model of manufacturing systems

atomic DEVS. Downstream model is defined by a basic parallel DEVS, because internal events and external events are likely to occur at the same time.

3.3.1 The upstream model

DEVS atomic model of upstream is presented in Fig. 4. In the model, we assume the states of receive1, send1, refuse1, send1, receive2, send2, refuse2, and send2 are so transient that they don't receive external events. When work pieces (manufacturing or remanufacturing work pieces) come, this model receives and stores different batches of work pieces. Upstream rejects batches when it reaches the maximum amount of queue. It will send the first one of queue to machine when it receives signal from machine. The definition of upstream model refers to Section 3.3.2.

3.3.2 The machine-detailed model

The framework of the machine is built with a DEVS atomic model. Different kinds and amounts of energy, input-output model can be used for analysis and description model variables. Sort, classify, and statistic energy consumption of fundamental data.

Machine receives work pieces and energy. Work pieces will be checked before proceeding firstly. Then, the qualified work pieces will be processed into finished products. At last, machine would export finished products and remaining energy.

(a) Formal description in DEVS of the machine model

$$\text{machine} = \{X_{\text{m}}, Y_E, S, \delta_{\text{int}}, \delta_{\text{ext}}, \lambda, \text{ta}\}$$

Input event variables: X_m=(energy, newWIP$_{\text{m}}$, Re-newWIP$_{\text{m}}$) 'energy' $\in R$, means energy imported from outside. energy $= \sum_{i=1}^{m} \int \text{ei}_i(t)\text{dt}$ (Suppose there are m kinds of input energy.). ei$_i(t)$ means energy input function.

- 'newWIP$_{\text{m}}$'$\in N^+$, means manufacturing work pieces. The amount is C.
- 'Re-newWIP$_{\text{m}}$'$\in N^+$, means re-manufacturing work pieces. The amount is C.

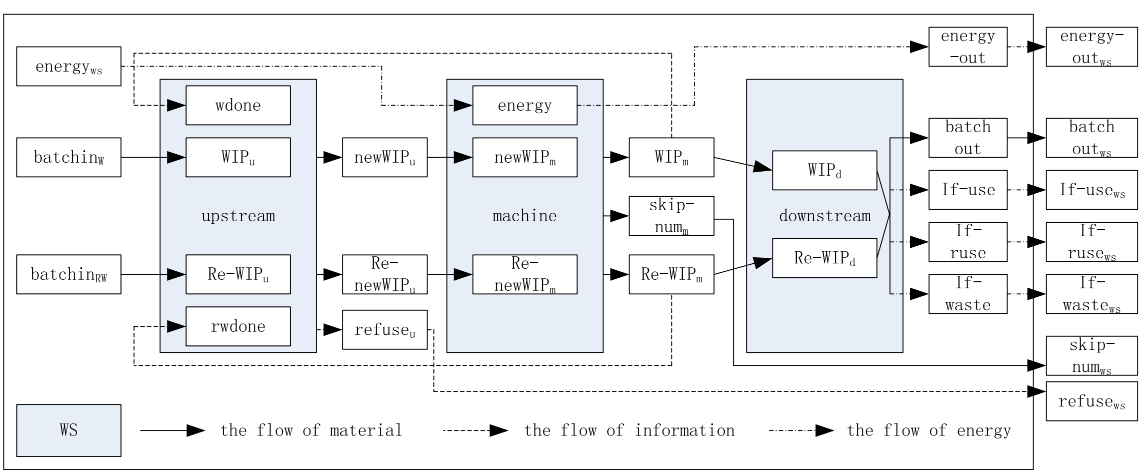


Fig. 3 The behavior of WS

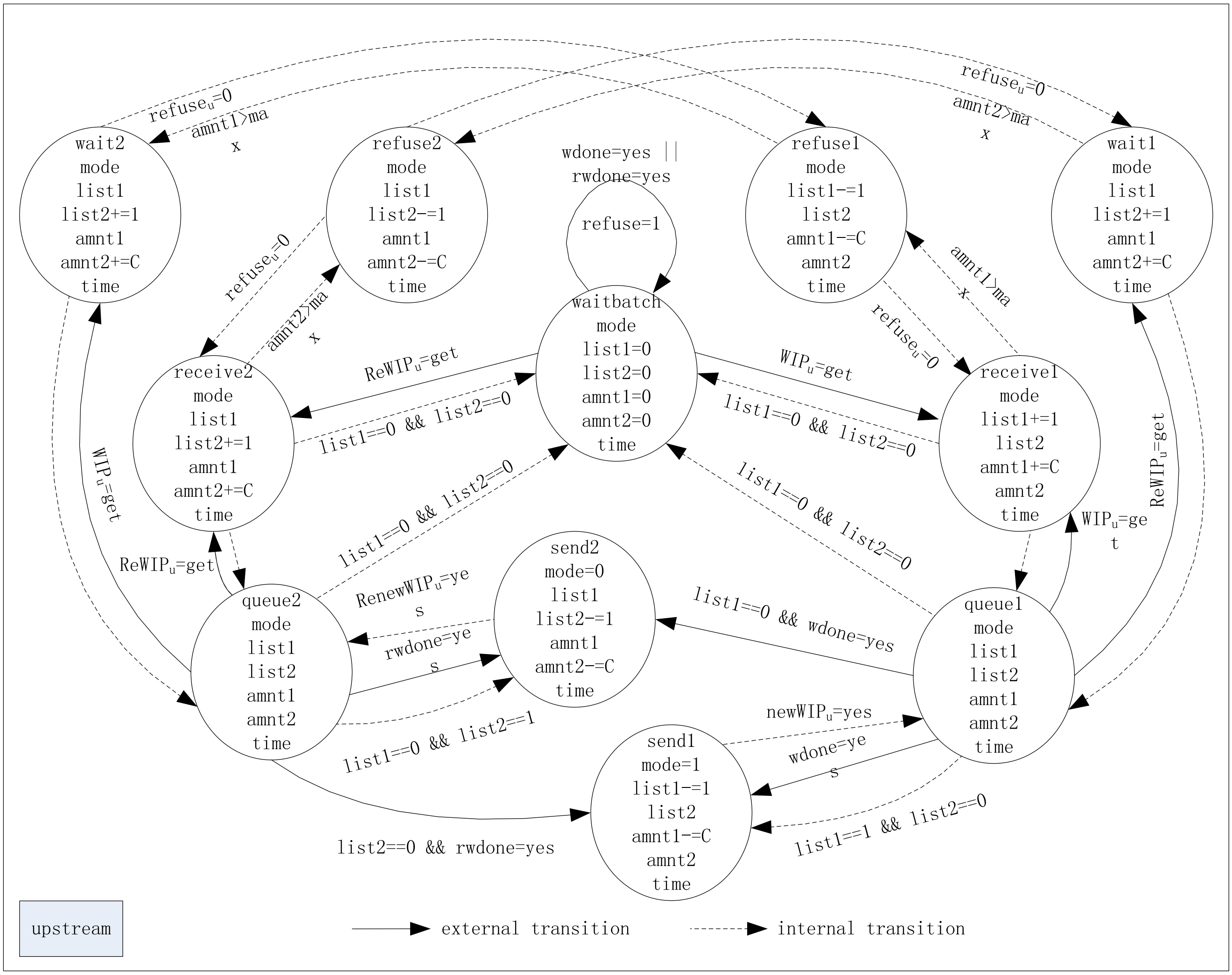


Fig. 4 DEVS atomic model of upstream

- Output event variables: Y_m=(WIP$_m$, Re-WIP$_m$, skip-num, energy-out).
- ‘WIP$_m$’={done}, indicates that manufacturing work pieces has been processed into finished products.
- ‘Re-WIP$_m$’={done}, indicates that remanufacturing work pieces have been processed into finished products.
- ‘skip-num’∈N, means unqualified work pieces before work pieces is going to be processed.
- ‘energy-out’∈R, means the remaining energy. energy-out = $\sum_{j=1}^{n}\int eo_j(t)dt$ (Suppose there are n kinds of output energy). $eo_j(t)$ means energy output function.
- State variables: S={phase}×mode×type×amnt×n-amnt×energy×σ, where
- ‘phase’={“wait”, “receive”, “queue”, “work”, “re-work”, “skip”} means the different states of ‘machine’.
- ‘mode’={0,1}, means batches of manufacturing and remanufacturing products. ‘mode=1’ means manufacturing products. While ‘mode=0’ means remanufacturing products.
- ‘type’={qualified, r-qualified, unqualified} indicates the product, which is a manufacturing/remanufacturing product, is qualified or not.
- ‘amnt’ ∈N means the amount of input products.
- ‘n-amnt’∈N means the amount of unqualified work pieces before work pieces are going to be processed.
- ‘energy’∈R means the amount of energy in its state. $e_i(t)$ means energy consumption function of No.i when machine is idle running. $we_i(t)$ means energy consumption function of No.i when machine proceeds with manufacturing work pieces. $rwe_i(t)$ means energy consumption function of No.i when machine proceeds with remanufacturing work pieces.
- ‘σ’∈R, which is ta(s), means the duration of the state.

(b) Interpretation of the machine behavior

DEVS atomic model of machine is present in Fig. 5.

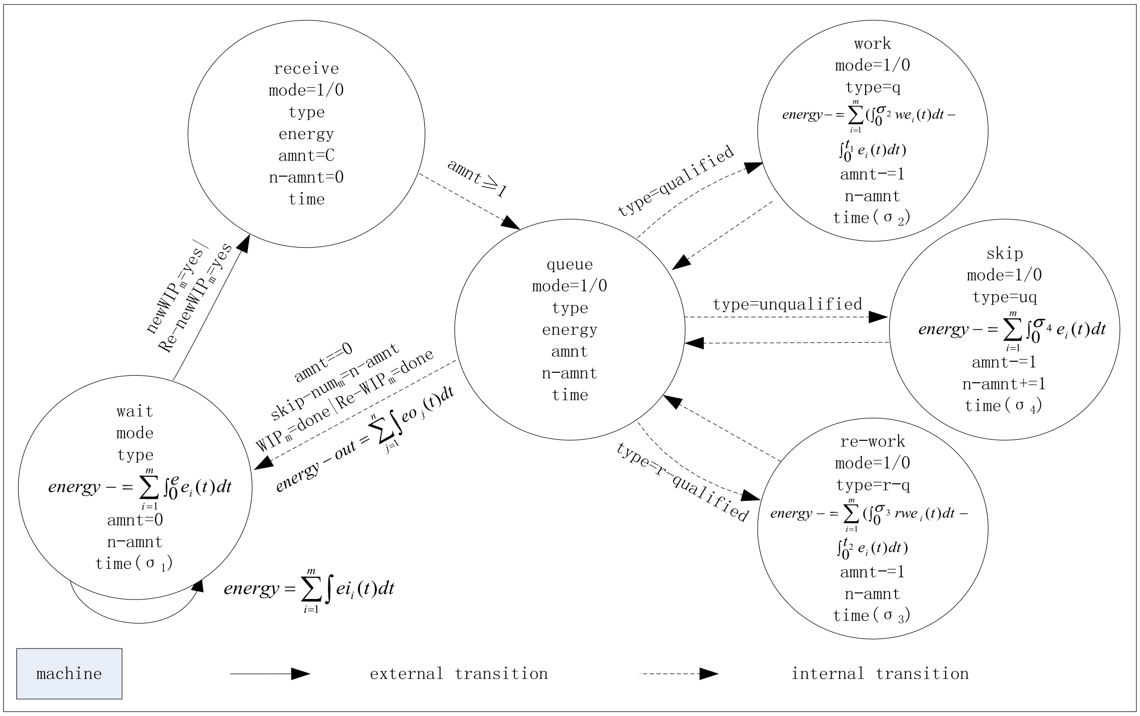


Fig. 5 DEVS atomic model of machine

Firstly, energy is imported into systems through input port of energy $\left(\text{energy} = \sum_{i=0}^{m}\int \text{ei}_i(t)\text{dt}\right)$; Let us assume that the initial set of model state is S = (“wait”, mode, type, energy- = $\sum_{i=1}^{m}\int_0^{e} e_i(t)\text{dt}$, amnt = 0, n-amnt, σ_1 = time(wait)) ($e \in \sigma_1$, is the duration of the wait). Secondly, when the external event occurs (newWIP$_m$=yes | Re-newWIP$_m$=yes), the state changes to S=(“*receive*”,0/1,*type*,*energy*,*amnt*=C,*n*−*amnt*=0, *time*). Because this state ‘receive’ is transitory, its variable ‘ta(receive)’ is set to 0, while the variable ‘energy’ remains unchanged. Then, a transition occurs when the variable ‘amnt≥1’ is met. The state changes to S=(“*queue*”,0/1,*type*,*energy*,*amnt*,*n*−*amnt*,*time*). The next step depends on the quality of the products. While ‘type=qualified && amnt≥1’, the variable ‘energy’ changes to energy- $= \int_0^{t_1} X dt$, before the state changes to S= (“*work*”, $0/1, q, energy- = \sum_{i=1}^{m}(\int_0^{\sigma_2} we_i(t)dt + \int_0^{t_1} e_i(t)dt)$, $amnt- = 1, n\text{−}amnt, time$). While ‘type=unqualified’, state changes to S= (“*skip*”, $0/1, uq, energy- = \sum_{i=1}^{m} \int_0^{\sigma_4} e_i(t)dt, amnt- = 1, n\text{−}amnt+ = 1, time$). The process of remanufacturing work pieces runs in the same way. At last, when the variable ‘amnt=0’ is met, state goes back to ‘wait’. Machine sends out messages, which contains ‘skip-num$_m$=n-amnt’, ‘WIP$_m$=done | newWIP$_m$=done’, ‘energy-out=energy’.

3.3.3 The downstream model

Parallel DEVS atomic model of downstream is present in Fig. 6. Downstream receives products from machine. Products would be classified according to the quality. This model would send out information of useful energy consumption, reuse energy and waste energy. When the state is checked, internal events and external events may occur at the same time. To solve this problem, we introduce Parallel DEVS atomic model, which has a confluent transition function (δ_{con}) which is an effective method. The definition of downstream model refers to Section 3.3.2.

3.4 The DEVS coupled model of WS

At the base of upstream, machine, downstream model, the DEVS coupled model of WS is built. Three models are linked by the flow of material, information, and energy (the flow of energy is highlighted), and send messages to each other by their interfaces.

3.4.1 Formal description in DEVS of WS

$$\text{WS} = \left(X, Y, D, \left\{M_d \middle| d \in D\right\}, \text{EIC, EOC, IC, Select}\right)$$

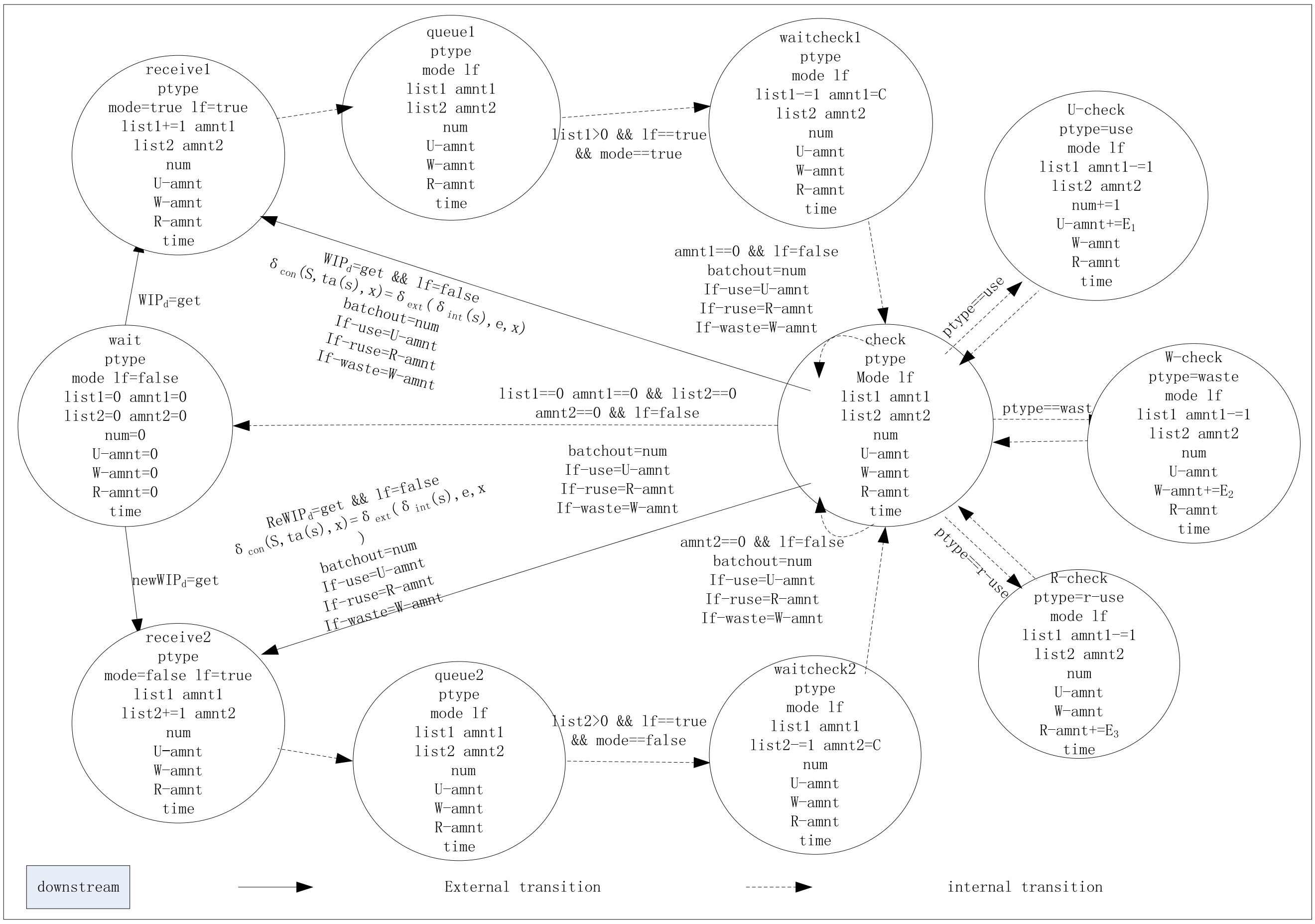


Fig. 6 Parallel DEVS atomic model of downstream

Input event variables: X=(batchin$_W$, batchin$_{RW}$, energy$_{ws}$), where

- ‘batchin$_W$’∈N^+, means manufacturing work pieces.
- ‘batchin$_{RW}$’∈N^+, means remanufacturing work pieces.
- ‘energy$_{ws}$’∈R^+, means total input energy.

Output event variables: Y=(energy-out$_{ws}$, batchout$_{ws}$, If-use$_{ws}$, If-ruse$_{ws}$, If-waste$_{ws}$, skip-num$_{ws}$, refuse$_{ws}$), where

- ‘energy-out$_{ws}$’∈R, means remaining energy, which is equal to ‘energy-out’ from machine.
- ‘batchout$_{ws}$’∈N, means total finished products, which is equal to ‘batchout’ from downstream.
- ‘If-use$_{ws}$’∈R, means useful energy consumption, which is equal to ‘If-use’ from downstream.
- ‘If-waste$_{ws}$’∈R, means waste energy, which is equal to ‘If-waste’ from downstream.
- ‘If-ruse$_{ws}$’∈R, means reuse energy, which is equal to ‘If-ruse’ from downstream.
- ‘skip-num$_{ws}$’∈N, means unqualified work pieces before work pieces are going to be processed, which is equal to ‘skip-num$_m$’ from machine.
- ‘refuse$_{ws}$’={0, 1}, ‘refuse$_{ws}$=0’ indicates the cache is so full that WS refuse to accept batches of products. ‘refuse$_{ws}$=1’ indicates there is no products.

A set of components: M={‘upstream’, ‘machine’, ‘downstream’}. The definition of components refers to Section 3.3.

EIC={((WS, ‘batchin$_W$’), (upstream, ‘WIP$_u$’)), ((WS, ‘batchin$_{RW}$’), (upstream, ‘Re-WIP$_u$’)), ((WS, ‘energy$_{ws}$’) , (machine, ‘energy’))}, link components and outside. In the same way, EOC={((machine, ‘energy-out’), (WS,‘energy-out$_{ws}$’)), ((downstream,‘batchout’), (WS,‘batchout$_{ws}$’)), ((downstream,‘If-use’), (WS,‘If-use$_{ws}$’)), …}.

IC={((machine, ‘WIP$_m$’), (upstream, ‘wdone’)), ((machine, ‘Re-WIP$_m$’), (upstream, ‘rwdone’)), ((upstream, ‘newWIP$_u$’), (machine, ‘newWIP$_m$’)),……}.

Select is the tie-breaking function.

3.4.2 Interpretation of the WS behavior

Logical behavior of WS is present in Fig. 3. Firstly, WS receives external events through EIC={((WS, ‘batchin$_W$’), (upstream, ‘WIP$_u$’))}, and stores them into the queue. Secondly, work pieces would be sent to machine through the link, which is IC={((upstream, ‘newWIP$_u$’), (machine, ‘newWIP$_m$’))}, between upstream and machine. Then, send products to downstream, sort energy consumption by the quality of products, and export products and the information through EOC={((machine, ‘energy-out’), (WS, ‘energy-out$_{ws}$’)), ((downstream, ‘batchout’), (WS, ‘batchout$_{ws}$’)), ((downstream, ‘If-use’), (WS, ‘If-use$_{ws}$’)), ……}. The process of remanufacturing work pieces runs in the same way.

4 Simulation analysis of a case study

A machinery manufacturing enterprises, which produces car parts, has many mechanic tool shops. At room temperature, specific cutting fluid and speed condition, there lists the data of the process of constant-velocity inner joint in Table 1, including rate of qualified products, the average power of idle running and running in the load, etc. By the way, the rates of qualified, unqualified, need-remanufacturing product are 98, 1.3, and 0.7 %.

4.1 Formal description in DEVS of the manufacturing system

The manufacturing system (MS) coupled DEVS is a structure.

$$\mathrm{MS} = \left(X, Y, D, \left\{M_d \middle| d \in D\right\}, \mathrm{EIC}, \ \ \mathrm{EOC}, \ \ \mathrm{IC}, \ \ \mathrm{Select}\right)$$

A set of components: M={M‘WS-1’, M‘WS-2’, M‘WS-3’, M‘WS-4’, M‘WS-5’, M‘WS-6’, M‘BS-1’, M‘BS-2’, M‘BS-3’, M‘BS-4’, M‘supply-energy’, M‘remaining-energy’, M‘Use-energy’, M‘Waste-energy’, M‘Reuse-energy’}. The definition of models refers to Section 3.

Logic behavior of MS is shown in Fig. 7. Products proceed from WS-1 to WS-6, which mean workstations shown in Section 3.4. BS-1 means the external cooperation, which process products with external conditions. BS-2 means the buffer stock of products. BS-3 means the total number of unqualified work pieces before work pieces are going to be processed. BS-4 means the set of refuse information from models (0 indicates the cache of WS-6 is so full that it refuse to accept batches of products. 1 indicates there is no products in WS-6.). Supply-energy indicates it supplies energy to MS. Remaining-energy is used for recycling energy. Use-energy, waste-energy and reuse-energy are used for adding up the amount of useful energy consumption, waste energy, and reuse energy. They send out the amount of different kinds of energy consumption for a batch of work pieces.

4.2 Design of the key parts of MS

On the basis of CD++ [24], which is a plug-in for Eclipse and a tool for Discrete Event modeling and simulation, the simulation of MS is shown referring to Appendix. The black square boxes mean the input or output port. The rectangular boxes, which are marked from WS-1 to WS-6, are DEVS coupled models of WS introduced in Section 3.4. The remains are DEVS atomic models. What is more, details of WS are present in Fig. 8. In order to simulate MS successfully, we suggest that the key parts are designed on the following principles:

Table 1 The process of constant-velocity inner joint

Process steps	Process	The average power of idle running /kw·h	Rate of qualified products from outside	The statistics of manufacturing products from a single facility			The statistics of remanufacturing products from a single facility			The average time of quality inspection/s	Remarks
				The average power /kw·h	The average process time/s	The average waiting time/s	The average power /kw·h	The average process time/s	The average waiting time/s		
1	Preparation	–	–	–	–	–	–	–	–	–	Sub-contractors
2	Drilling	1.15	95 %	2.3	35	8	2.1	25	10	6	
3	Hobbing	–	–	–	–	–	–	–	–	–	Sub-contractors
4	Heat treatment	–	–	–	–	–	–	–	–	–	Sub-contractors
5	Grinding	4.8	98 %	9.2	40	8	8.6	33	10	6	
6	Turning	5.6	95 %	11.3	21	8	10.8	13	6	6	
7	Grinding six groove	5.1	98 %	10.6	112	8	9.8	53	6	6	
8	Internal grinding	1.8	98 %	3.9	40	8	3.3	31	10	6	
9	Hole processing	0.34	95 %	0.80	5	8	0.77	5	6	6	
10	Inspection Cleaning	–	–	–	–	–	–	–	–	–	Sub-contractors
11	Assembly	–	–	–	–	–	–	–	–	–	Workers

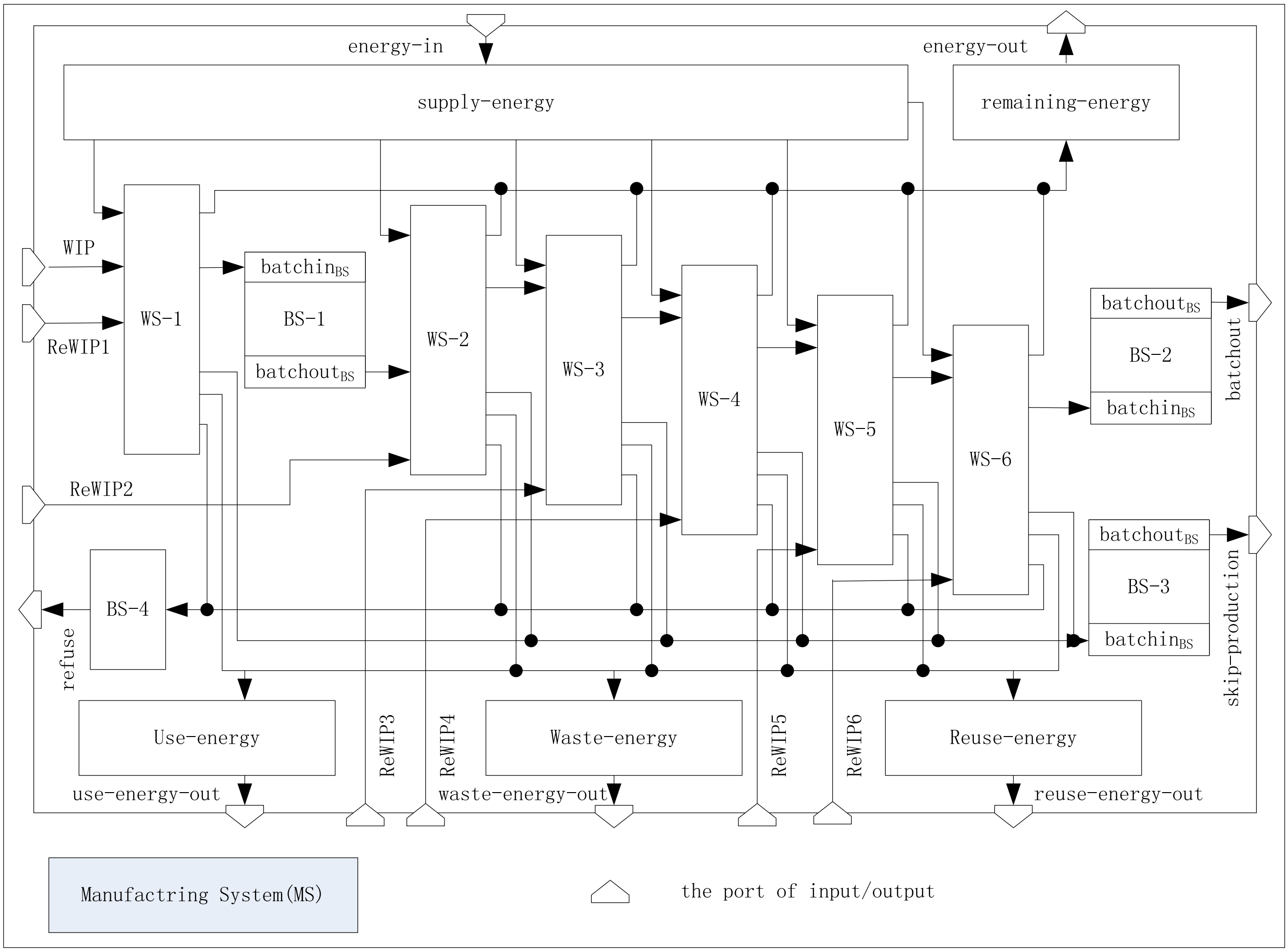


Fig. 7 Logic behavior of MS

- M‘supply-energy’ is used for supplying energy to MS. We suppose that this model supplies so much energy that MS could run normally. In simulation process, the ‘ei’ port of WS is set to 0 (Fig. 8). The ‘eo’ port of WS means the total amount of energy consumption. So, M‘remaining-energy’ achieves statistic of energy consumption of the whole process.

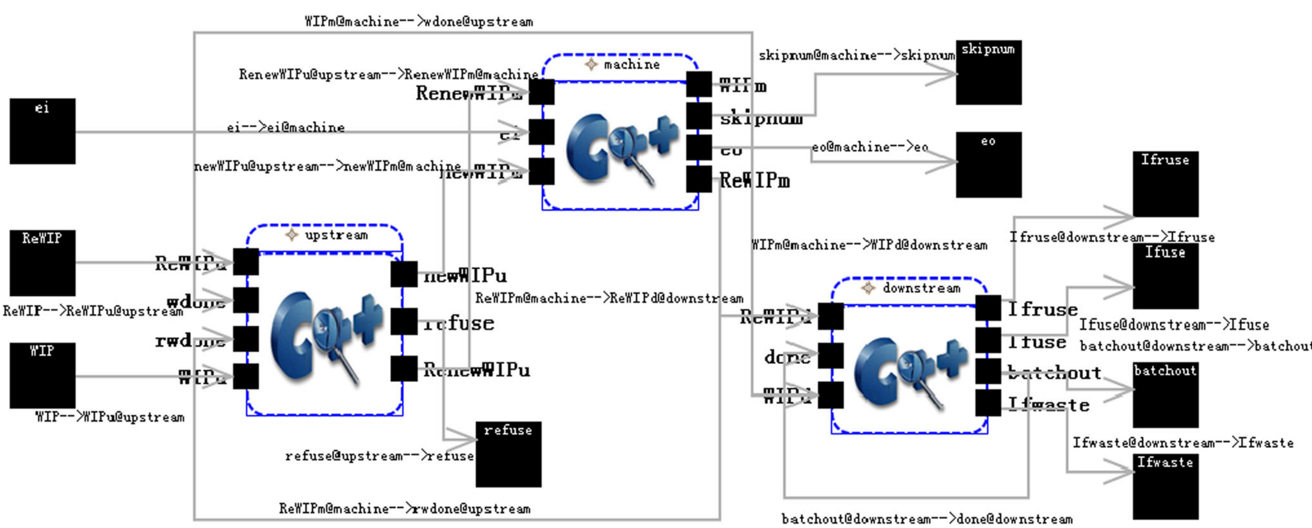


Fig. 8 The simulation of WS

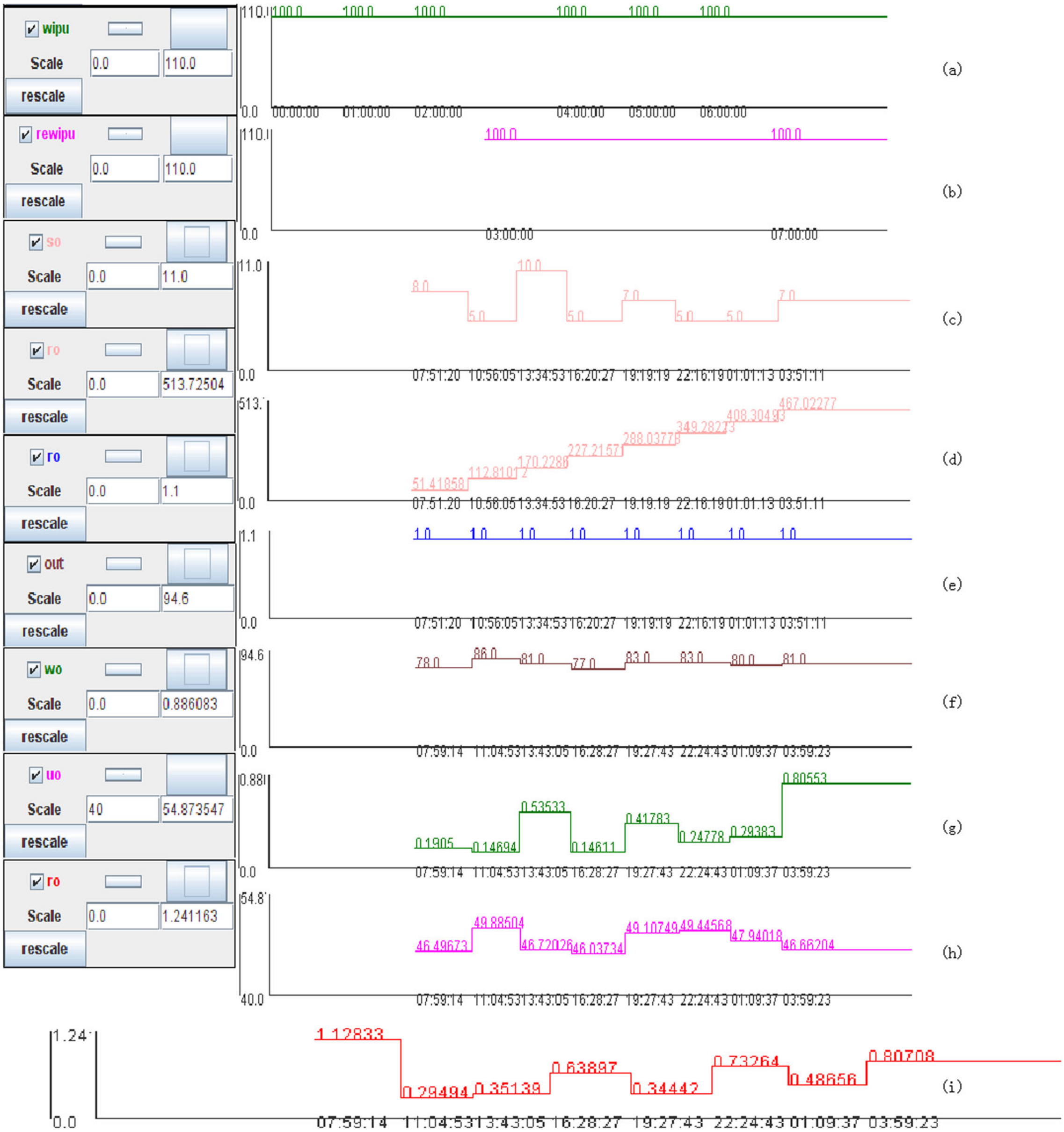


Fig. 9 The value of input-output ports in MS

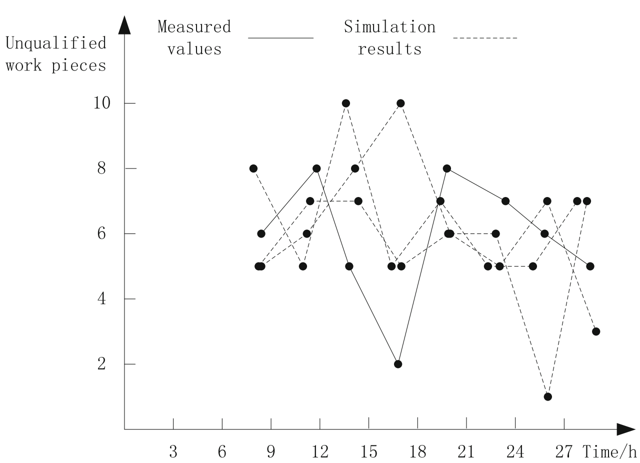


Fig. 10 The amount of unqualified work pieces before work pieces

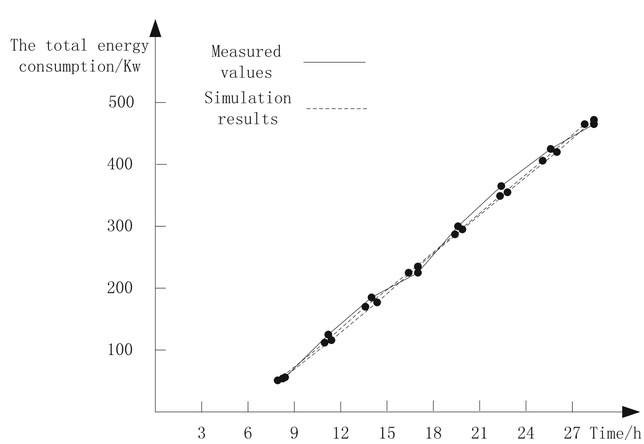


Fig. 11 The total energy consumption

- Work pieces will be checked before proceeding with manufacturing products and remanufacturing products firstly in M‘WS-1’and M‘WS-2’. However, work pieces will only be checked before proceeding with remanufacturing products in M‘WS-3’, M‘WS-4’, M‘WS-5’, and M‘WS-6’.
- The machine in WS, which is from WS-1 to WS-6, starts to run when the first batch of products reaches to each machine. They wouldn’t stop until the simulation is ended.
- The energy consumption of transient state in WS is ignored, such as ‘receive’ and ‘queue’ in machine. The energy consumption function of machine in WS can be designed in different ways [6–8, 25–27]. In this paper, energy consumption function is obtained by statistical methods [26, 27].
- The method, which is used for determining whether the product is qualified, is achieved by that system generates a random number between 0 and 1. The product is qualified when the random number is within limits. The batches of products are importing continually. Energy consumption continues to accumulate, and doesn’t stop until the last product is finished.

4.3 Simulation results of MS

According to on-site conditions, 100 work pieces are imported into MS. There are remanufacturing work pieces in the third, seventh hours. The values of input-output ports are shown in Fig. 9.

At the beginning, Fig. 9a illustrates that 100 work pieces are imported into MS through input port of ‘WIP_u’. Then, work pieces are finished in machine at 7:51:20. At the same time, MS exports eight unqualified work pieces before work pieces are going to be processed in Fig. 9c, 51.41858 kw energy consumption (including the total energy consumption in standby and processing in 7:51:20) in Fig. 9d. ‘refuse=1’ in Fig. 9e indicates that upstream in WS-6 has no buffer stock. At last, the inspection of products finishes at 7:59:14. MS exports 78 qualified products in Fig. 9f, 46.49673 kw useful energy consumption in Fig. 9h, 1.12833 kw reuse energy in Fig. 9i, and 0.1905 kw waste energy in Fig. 9g. What is more, useless energy consumption is 3.60302 kw, which can be got by $51.41858-46.49673-1.12833-0.1905=3.60302$ kw. The remaining process can be analyzed in the same way.

The amount of unqualified work pieces before process between measured values and simulation results is present in Fig. 10. Three groups of simulation results (the dotted lines in Fig. 10) are shown, such as five unqualified work pieces at 8:21:00, eight unqualified work pieces at 7:51:20, and five unqualified work pieces at 8:19:53. And one group of measured values (the solid line in Fig. 10) is shown, such as six unqualified work pieces at about 8:20:00. The margin of error about time and values is acceptable. We can get the remaining data in the same way.

The total energy consumption between measured values and simulation results is present in Fig. 11. Two groups of simulation results (the dotted lines in Fig. 11) are shown, such as 51.4186 kw energy consumption at 7:51:20 and 54.5473 kw energy consumption at 8:19:53. And one group of measured values (the solid line in Fig. 11) is shown, such as 55 kw energy consumption at about 8:20:00. The margin of error about time and values is acceptable. What is more, the analysis of qualified products, useful energy consumption, waste energy and etc. can be done in the same way.

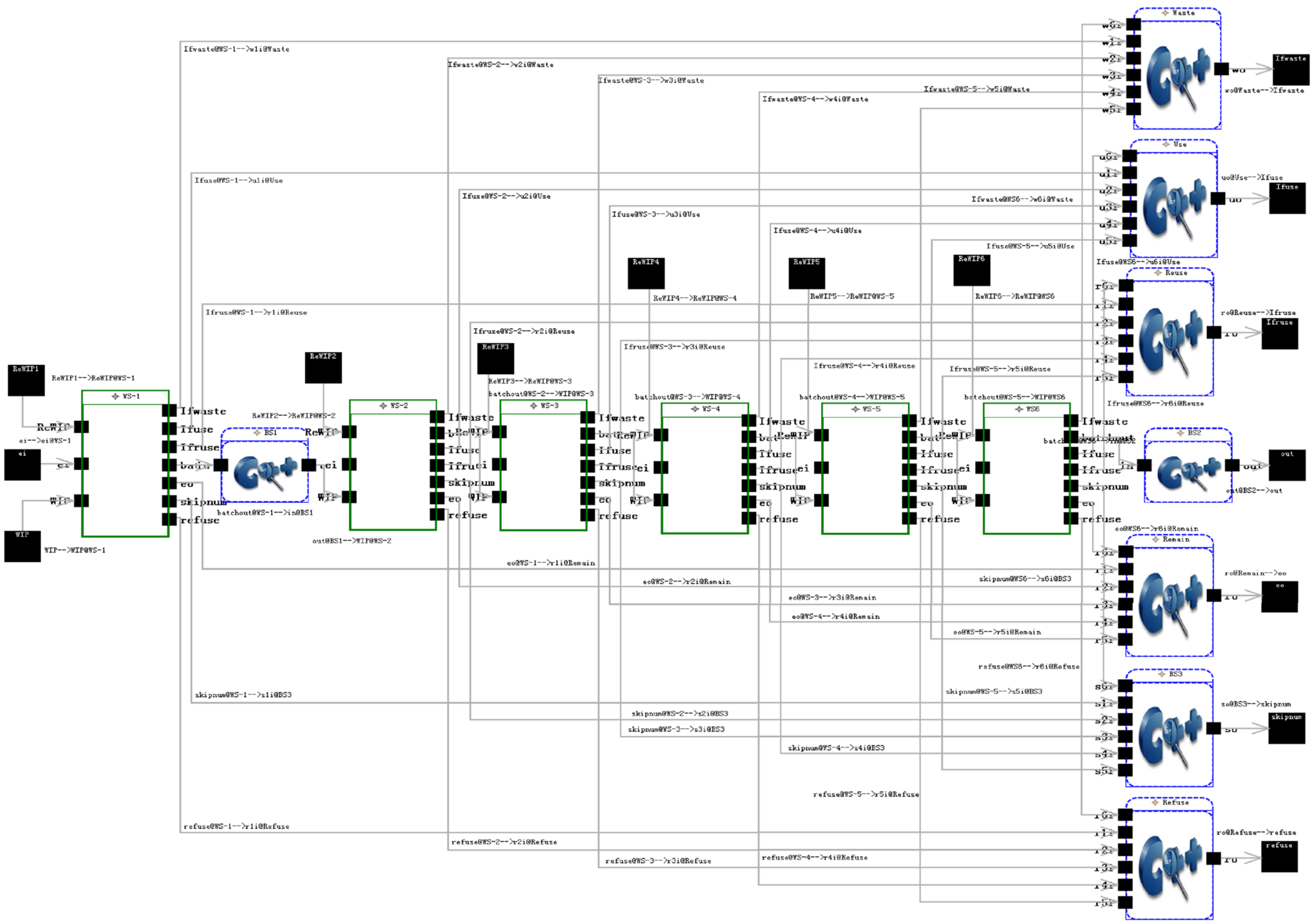
5 Conclusion

In this paper, we put forward an energy consumption model for manufacturing/remanufacturing systems to achieve lean energy, and simulated this model with CD++. This paper mainly analyzes integration logical process of manufacturing/remanufacturing systems. Then energy consumption model was built with the theory of DEVS and input-output model. It described the basic processing unit of the manufacturing system—WS, WS received some waiting for the work piece and energy, the output of products and different energy consumption information. In the process of modeling, the emphasis analyses manufacturing/remanufacturing of integration machining process and material flow, information flow, energy flow of the coupling process to describe the change of system state in machining process. It classified the energy consumption according to the quality of the products. Finally, comparing the measured values with simulation results, the energy model in this paper was proved to be reasonable. The model in this paper not only can provide reference for design and optimization of components and parts, but also provide theoretical support for energy statistics, and enrich the content of Green Manufacturing. It can also analog simulation for unpredictable random events, and has strong reusability and portability. The next stage of the research will consider environmental impact indicators into the energy model, and develop more meaningful software platform.

Acknowledgments This research is sponsored by the National Science Foundation of China (nos. 51275365 and 51475340) and National High-tech 863 Program (no. 2014AA041504), Key Laboratory for Metallurgical Equipment and Control of Ministry of Education, Wuhan University of Science and Technology (grant no. 2013A12).

Appendix

The simulation of MS in CD++



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