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Therblig-embedded value stream mapping method for lean energy machining

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Abstract: To improve energy efficiency, extensive studies have focused on the cutting parameters optimization in the machining process. Actually, non-cutting activities (NCA) occur frequently during machining and this is a promising way to save energy through optimizing NCA without changing the cutting parameters. However, it is difficult for the existing methods to accurately determine and reduce the energy wastes (EW) in NCA. To fill this gap, a novel Therblig-embedded Value Stream Mapping (TVSM) method is proposed to improve the energy transparency and clearly show and reduce the EW in NCA. The Future-State-Map (FSM) of TVSM can be built by minimizing non-cutting activities and Therbligs. By implementing the FSM, time and energy efficiencies can be improved without decreasing the machining quality, which is consistent with the goal of lean energy machining. The method is validated by a machining case study, the results show that the total energy is reduced by 7.65%, and the time efficiency of the value-added activities is improved by 8.12% , and the energy efficiency of value-added activities and Therbligs are raised by 4.95% and 1.58%, respectively. This approach can be applied to reduce the EW of NCA, to support designers to design high energy efficiency machining processes during process planning.

JEL-codes: Q47 Energy Forecasting; Q49 Other

Key words: energy efficiency; lean energy machining; value-added; non-valued added; Therblig-embedded value stream mapping.

1. Introduction

Nowadays, rising energy prices and increasing environmental awareness are driving manufacturing companies to prioritize green manufacturing [1]. Besides classical economical production objectives (e.g., time, quality, and cost), environmentally driven objectives, such as high energy efficiency, low carbon emissions, etc., have become increasingly relevant for the manufacturing industry [2-4]. Producing more products or services with less material, energy, etc., is becoming a new challenge faced by manufacturing companies, which are trying to find new ways to reduce energy consumption to minimize costs and environmental impact [5,6]. Driven by the development of technology, machine tools are increasingly integrated, efficient and intelligent, leading to growing energy consumption. The report of the Energy Information Administration (EIA) shows that machining electricity consumed in manufacturing accounted for 90% of the electricity consumption in the industry and 75% of electricity consumption in manufacturing as a whole [7]. An interesting study conducted by Gutowski showed that CO_2 emissions of one computer numerical control (CNC) machine tool (22 kW spindle power) in one year is equivalent to that of 61 SUVs' CO_2 emissions (20.7 mpg, 12000 miles/year) [8]. China owns about eight million machine tools, which ranks them number one in the world [9]. As shown in Fig. 1, if one machine tool can process 1000 parts/day and 0.01kWh can be saved machining one part, then the total potential energy savings could be more than 20 TWh/year, which is about 24% of the Three Gorges Power Station's actual annual generation capacity [10]. On a larger scale, the potential energy savings represents 0.66% of the total electricity consumption of the manufacturing industry in China [11]. Although the proportion is not very large due to the size of the industry, the total energy savings potential is still considerable.

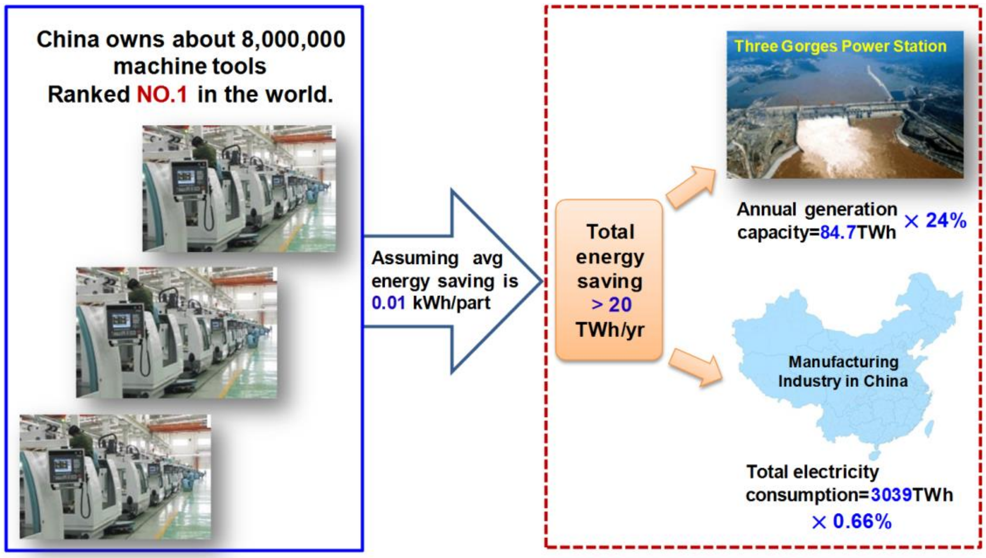


Fig. 1. Total energy saving potential of machine tools in China.

It is clear that the machining process has become one of the major sources of energy consumption and environmental impacts of the manufacturing industry. Unfortunately, machining, as a manufacturing process to remove extra material, is wasteful in its use of energy and very inefficient [12-16]. The energy used for the direct removal material is generally less than 30% of the total energy consumed by a machine tool [17-19]. Therefore, the energy-saving potential in the machining process is enormous.

The study of energy modeling and energy efficiency improvement of the machining process has aroused extensive interest in recent years[20-25]. To achieve better energy management of the machining process, energy consumption allowance, as a significant management tool for improving energy efficiency, was introduced into the mechanical manufacturing industry [26]. Moreover, many studies have focused on optimizing the cutting parameters in the machining process [27-38]. It is necessary to point out that apart from cutting activities, non-cutting activities (NCA) occur frequently during machining [39] and the energy demand of NCA is significant, sometimes using more than 70% of the total energy consumption in machining [40]. Therefore, this is a promising way to achieve energy saving and lean energy machining through optimizing NCA without changing the material cutting parameters. Lean energy machining is defined as machining more material with less energy without lowering the machining quality.

In this paper, machining process refers to conventional machining processes, i.e., turning, milling, etc. The machining process can be defined as the process of removing material from a workpiece in the form of chips [41].The main aim of the machining process is removing material to obtain a designed shape of a workpiece. As shown in Fig. 2, the machining process can be divided into two types of activity: value-added activity (VAA) and non-value added activity (NVAA). The VAA is defined as the activity which directly removes material, while the activity that does not create value and does not directly remove material, can be defined as NVAA (e.g., standby operating, rapid positioning, etc). A significant amount of energy is consumed by the non-cutting activities which are considered NVAA. Energy consumption for the actual cutting process (VAA) is generally less than 30% of the total energy consumption of machine tools [42,43]. For only some modern milling machine tools, this proportion can reach up to 65.8% [44]. Hence, there is great potential for improving the energy efficiency of the machining process through energy-saving in NVAAs. The energy optimization of material cutting activities has drawn much attention from researchers [27-38]. However, it is difficult for the existing methods to accurately determine and reduce the energy wastes in NVAA. To bridge this gap, a Therblig-embedded Value Stream Mapping (TVSM) method for lean energy machining is proposed in this paper. This method can improve the transparency of energy demand in the machining process and identify potential energy saving opportunities in NVAA. The advantages of this method are: 1) the machining quality is not affected as the cutting parameters are not unchanged; 2) energy savings can be achieved without shortening the service life of the cutting tool; 3) the energy demand of NVAA occupies a large proportion of the total energy of the machining process and the energy saving potential is significant ; 4) the approach can support the designers to help them design a high energy efficiency machining process.

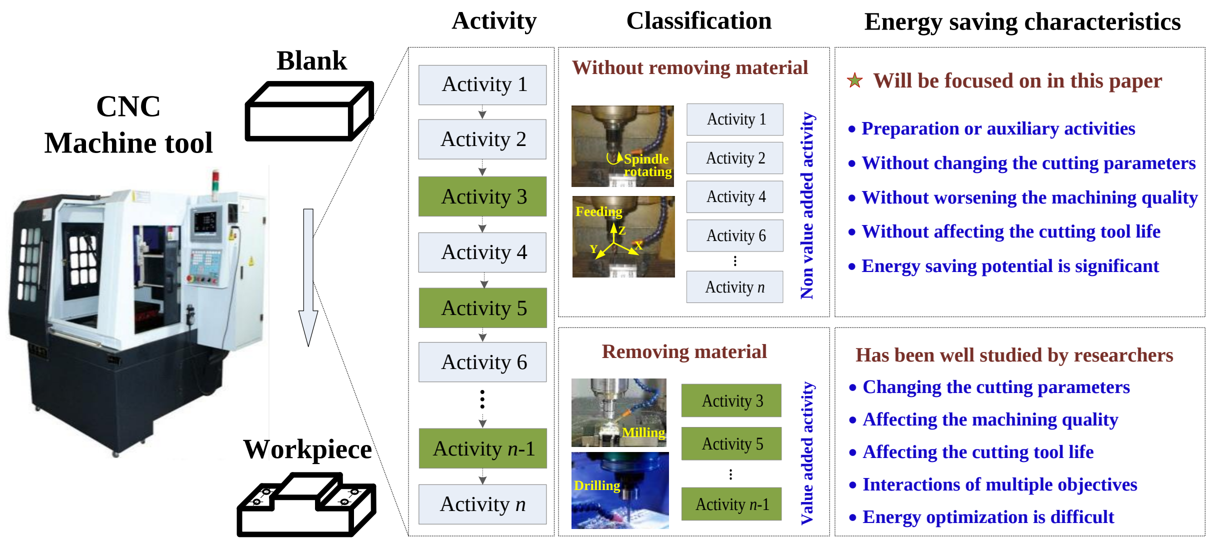


Fig. 2. Classification of machining activities and corresponding energy saving characteristics.

2. Literature review

Substantial research has been conducted on energy saving issues in the machining process. Most studies have primarily focused on energy consumption monitoring [45-48], energy consumption and carbon emission modeling [49-55], and simulations for saving energy [56-59]. In addition, improving the machine tool itself has been identified as an effective way to save energy. For instance, lightweight design [60], multi-spindle systems [61], and kinetic energy recovery systems [62] are common energy-saving designs. The experiments also showed that significant energy savings can be achieved with these designs. However, this method only applies to the design stage. Once in use, applying these designs to a machining tool is extremely difficult due to time constraints and the high cost. Therefore, optimization of scheduling and optimization of cutting parameters are more practical measures for energy savings once the machine tool is operating.

When optimizing scheduling, energy consumption is usually not considered in the traditional scheduling issues. Recently, some references focused on the scheduling problem with considering energy factor [63]. Fang presented a mathematical programming model of the flow shop scheduling problem that considers peak power load, energy consumption and associated carbon footprint in addition to cycle time [64]. An energy-aware scheduling model of manufacturing processes was proposed by Bruzzone [65]. Shrouf proposed a mathematical model to minimize energy costs for single machine production scheduling [66]. Liu developed a multi-objective scheduling method with reducing energy consumption as one of the objectives [67]. Due to the computational complexity of scheduling problem itself, the power models in the above researches are generally simplified models. The power profile obtained based on the simplified power models is often not consistent with the actual power profile.

For the optimization of cutting parameters, Aggarwal investigated the effects of cutting parameters on power consumption by using the response surface methodology (RSM) and Taguchi's technique [68]. Results showed that cutting environment is the most significant factor followed by cutting speed and depth of cut. Campatelli provided an experimental approach to optimize the process parameters in order to minimize the power consumption in a milling process [69]. It was showed that energy saving can be achieved if the maximum allowable value of feed and depth of cut are selected [70]. The reason this occurs is mainly because the cutting tool life and machining quality were not taken into account. Achieving greater energy efficiency with this method may result in the worsening of other factors such as quality [6]. Bhushan pointed out that it is important to minimize power consumption and maximize tool life during machining [71]. Therefore, the cutting parameters such as cutting speed, feed rate, depth of cut and nose radius are optimized by multi-response considerations namely power consumption and tool life. It is necessary to note that changing cutting parameters will affect the machining quality. Therefore, the optimization of the cutting parameters is a multi-objective optimization problem, surface roughness should be taken into account [72]. An experimental study was carried out to ensure that the energy consumption and surface roughness were minimized, while the material removal rate was maximized [73]. Most research about the optimization of cutting parameters has mainly focused on the material cutting state or treated the power consumed as the unloaded power to simplify the optimization problem [72]. Actually, energy consumption at the material cutting stage is not the main part of the total energy consumed, while NCA accounts for the majority of the energy consumed in the machining processes at more than 70% of the total [43,40]. Therefore, improvement opportunities exist in the NCA portion of the machining process.

As mentioned above, substantial energy is consumed by NVAA during the machining process. There is limited research on eliminating or reducing the energy of NVAA by using value stream analysis. In our previous work, we indicated that Therblig-embedded value stream mapping can be applied for energy saving in the machining process [74]. Some researchers tried to combine sustainable metrics with value stream mapping (VSM) and a Sustainable-VSM tool was proposed, which includes metrics to evaluate the environmental and societal performance of a manufacturing line [75]. Three case studies were conducted to demonstrate the applicability of the Sustainable-VSM tool [76]. Similarly, an economic and environmental value stream map (E^2VSM) method was proposed for modeling multi-product manufacturing systems with dynamic material, energy and information flows, and the proposed methodology was validated with an industrial case study [77]. Another relevant study was conducted by Mustafaraj [78]. They developed a method for determining auxiliary and value-added electricity in manufacturing operations. The sampling rate of date collection was set to 15 minutes. Due to the large sampling rate and batch production mode, the approach did not provide deep insight into the energy consumption of each machining activity for each product and some energy efficiency improvement opportunities may have been missed. To fill this gap, a TVSM method is proposed in this paper. This method can provide further insight into energy usage in the machining process, identify the value-added and non-value-added activities, and further distinguish value-added and non-value-added Therbligs in activities. Consequently, this method can help to determine the sources of energy wastage (non-value-added activities and Therbligs) and eliminate them by implementing a future state value stream, without changing material cutting parameters. Hence, energy savings in a machining process can be achieved without lowering the machining quality, which is exactly the aim of lean energy machining.

3. Therblig-embedded value stream mapping method

Lean manufacturing focuses on eliminating waste, simplifying procedures and speeding up production [79]. The key principles of lean are continuously and relentlessly improving the value, value stream, flow, and pull in business operations [80]. In this paper, a TVSM method is proposed to realize lean energy machining.

The framework of the proposed method is shown in Fig. 3. The approach can be divided into two main parts: machining process analysis and value stream analysis. More specifically, machining activities are identified according to the NC program and then each activity is further decomposed into Therbligs, which is the basic energy demand unit, based on mapping the relationship between activities and Therbligs. Based on the machining process analysis, the current-state-map (CSM) of TVSM can be established, with which energy wastes are easily to be identified. Therefore, the energy wastes can be reduced or eliminated by implementing a Future-state-map (FSM).

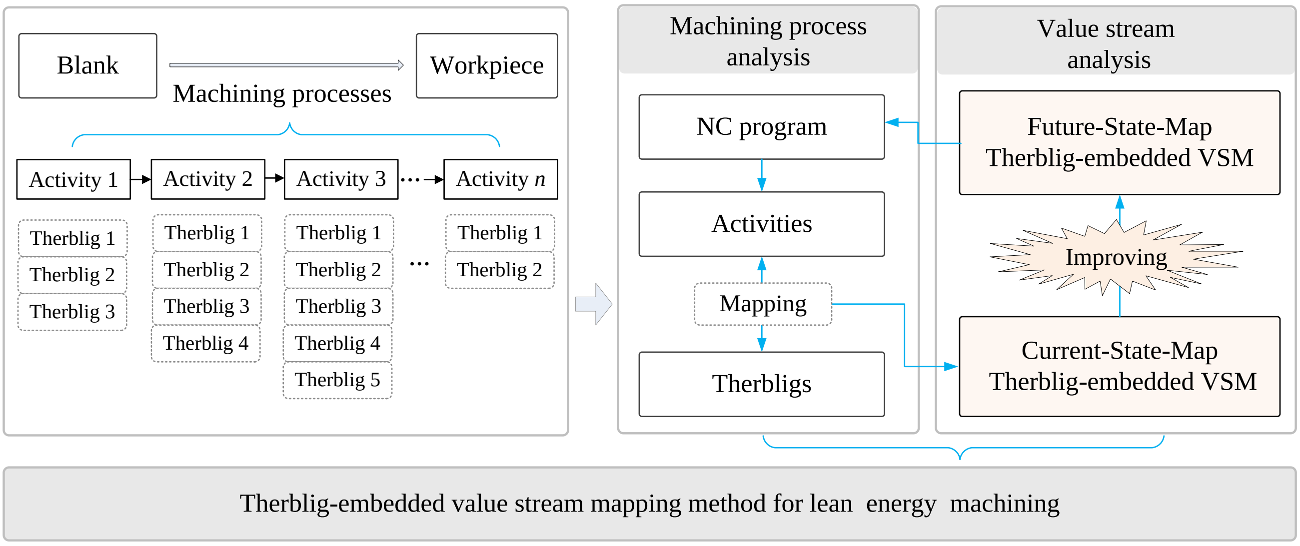


Fig. 3. Framework of the proposed methodology.

3.1. Value stream mapping

Value Stream Mapping (VSM) has emerged as the preferred way to implement lean in recent years. VSM is an extremely powerful tool used to describe the configuration of value streams [80,81]. It not only maps material flows but also information flows that signal and control these material flows [82]. It can help us to see and to understand the flow of material and information as a product makes its way through the value stream [83]. Components of traditional VSM is shown in Fig. 4 [80,83].

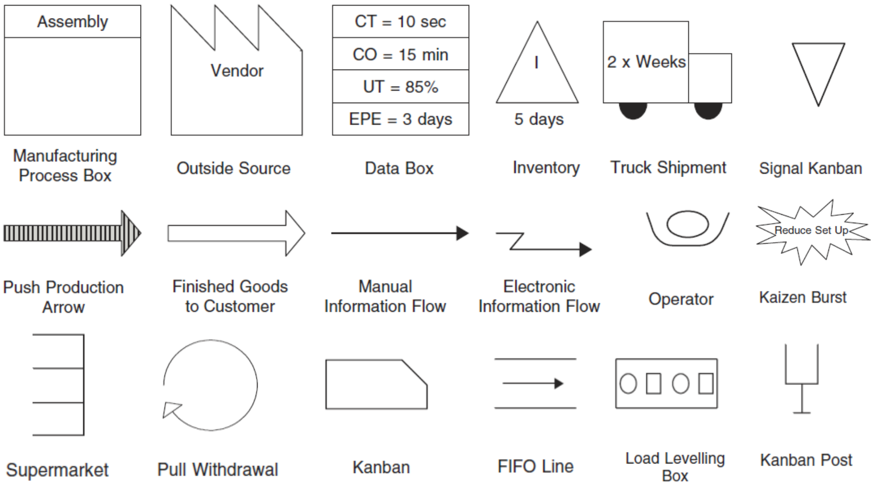


Fig. 4. Components of a traditional value stream map [80].

3.2. Lean energy machining based on Therblig-embedded value stream analysis

The TVSM approach can be demonstrated through seven subparts, as shown in Fig. 5. The specific content of each subpart is shown in the following parts of this section.

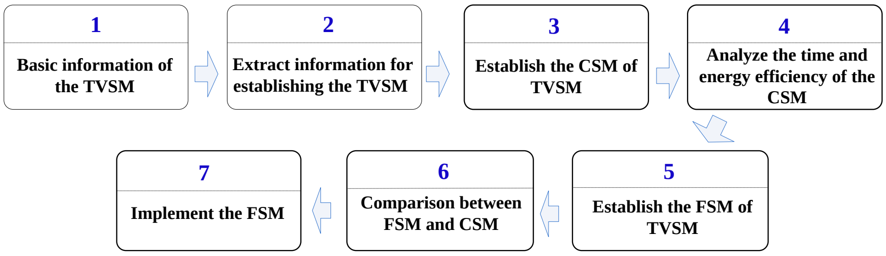


Fig. 5. Procedure of the Therblig-embedded value stream mapping.

3.2.1. Basic information about the TVSM

VSM can help us visualize the value flow and see the waste as well as the sources of waste in value stream. Once "value" has been defined, lean production development requires the analysis of the ‘value stream’, with all activities-both value-added and non-value-added [84]. Machining activities can be further decomposed into basic Therbligs of machine tools [85,74]. From the point of view of lean energy, Therbligs of machine tools can also be divided into two types: value-added Therbligs and non-value-added Therbligs. As mentioned previously, the main aim of machining process is to remove material and shape the workpiece. Therefore, only Therbligs directly removing material create value, which are defined as value-added Therbligs (VATs). Therbligs that do not create value (not directly removing material) are defined as non-value-added Therbligs (NVATs). Notably, not all NVATs are sources of energy wastes and require elimination. Actually, the NVATs can be classified into two types: Necessary NVAT (N-NVAT) and Unnecessary NVAT (U-NVAT). N-NVAT denotes Therbligs that do not create value but are necessary for the machining process; U-NVAT denotes Therbligs that do not create value and are therefore not required. A TVSM method is proposed by combining Therbligs with traditional VSM. VSM provides a set of standard components as a common language for describing manufacturing processes[80]. To conduct energy analysis, TVSM further extends these components and the main components of the TVSM are shown in Fig. 6.

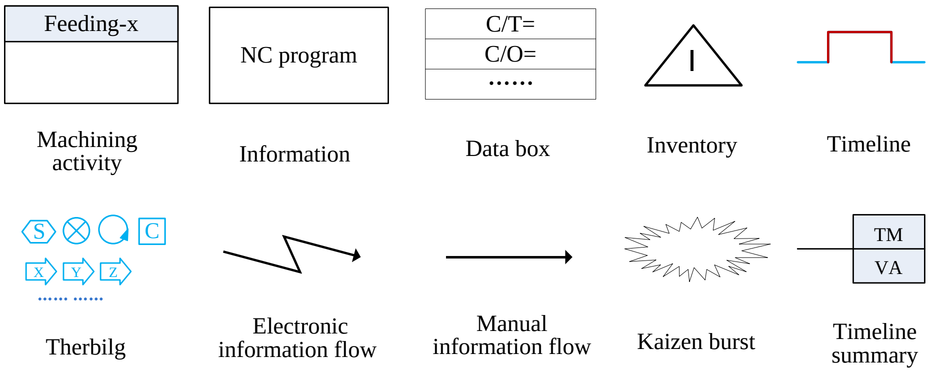


Fig. 6. Main components of Therblig-embedded value stream map.

3.2.2. Extracting information for establishing the TVSM

Machining activities are composed of Therbligs, and when the Therbligs in an activity contains value-added Therbligs, the activity is considered a value-added activity (VAA). The VAA can also contains non-value-added Therbligs and those NVATs can be reduced or eliminated. When all the Therbligs in an activity are non-value-added Therbligs, the activity is a non-value-added activity (NVAA). Similarly, the NVAAs can be classified into two types: Necessary NVAA (N-NVAA) and Unnecessary NVAA(U-NVAA). If some Therbligs in an activity can be eliminated or reduced in terms of duration and power, the corresponding activity cannot be eliminated but can be optimized, which is called N-NVAA. If all the Therbligs in an activity can be eliminated, then the corresponding activity can be eliminated, which is called an U-NVAA.

TVSM can be used to determine value-added Therbligs and activities and non-value-added Therbligs and activities, and highlight the sources of energy waste (U-NVAT and U-NVAA). Value stream analysis can be conducted to eliminate or optimize the waste activities or Therbligs and increase the proportion of VAT and VAA during a machining process. Consequently, the energy efficiency of a machining process can be improved..

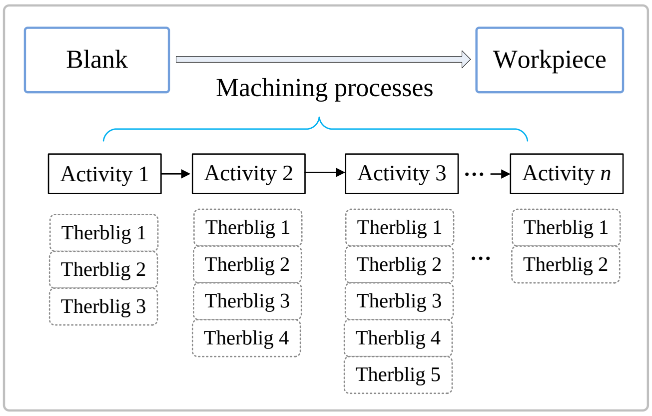


Fig. 7. Composition of machining processes.

Machining processes can be decomposed into a series of activities and each activity is composed of one or more basic Therbligs (see Fig.7). The activity extraction method and mapping relationship between activities and Therbligs have been researched in our previous work [85,86]. The activities of an actual machining process, duration, and corresponding Therbligs of each activity can be obtained. Supposing *n* activities are decomposed from one machining process, the duration and corresponding Therbligs of each activity can be listed in a table, as shown in Table 1.

Table1

Extracted activities and corresponding Therbligs.

No	Activity	Duration(s)	Corresponding Therbligs
1	Activity 1	5.00	Therblig-SO⟨S⟩;-L⊗
2	Activity 2	1.50	Therblig-SO⟨S⟩;-L⊗;-SR◯;
…	……	……	……
n-2	Activity *n*-2	4.75	Therblig-SO⟨S⟩;-L⊗;-SR◯;-XF X▷;-MC $\boxed{C}$
n-1	Activity *n* -1	0.36	Therblig-SO⟨S⟩;-L⊗;-SR◯;-XF X▷
n	Activity *n*	6.45	Therblig-SO⟨S⟩;-L⊗;-SR◯;-XF X▷;-ZF Z▷;-MC $\boxed{C}$

3.2.3. Establishing the CSM of TVSM

According to the information in Table 1, TVSM can be established with the components depicted in Fig. 8. The establishment steps of TVSM are listed as follows.

Step one: Establish the activity chain

Activity chain can be established according to the extracted activities and sequence of activities in Table 1. Activities in the activity chain are connected by information flow, electronic and manual, as shown in Fig. 8a. For CNC machine tools, the machining activities are controlled by computer, and information flow between two activities is therefore electronic information flow.

Step two: Embed Therbligs into activity

Based on the established activity chain and the relationship between activities and Therbligs, Therbligs are embedded into each activity in a value stream map, as shown in Fig. 8b. To clearly distinguish value-added Therblig from non-value-added Therbligs, the value-added Therblig (Therblig-MC $\boxed{C}$) is described in red, while non-value-added Therbligs (Therblig-SO ⟨S⟩; -L ⊗; -CFS ≋; -CC ⊔; -SR ◯; -XF X▷; -YF Y▷; -ZF Z▷; -AR ↺A ; -BR ↺B ; -CR ↺C ; -TS ↲1; -TC 1↲2) are described in blue. The activity which contains value-added Therblig is a VAA.

Step three: Add a data box

Corresponding data box is added under each activity, in which cycle time (C/T) and changeover time (C/O) of activity are listed, as shown in Fig. 8b. C/T denotes the duration of each activity and C/O denotes the preparation time for each activity.

Step four: Draw timeline

After adding the data box, a timeline is drawn under each data box according to the C/T and type of activity. To be specific, when the activity is a VAA, the timeline is drawn in red; otherwise, the timeline is drawn in blue, as shown in Fig. 8c. Moreover, the C/T value for the corresponding activity is labeled on the timeline.

Step five: Fill in the timeline summary

According to the timeline of each activity, the Total Machining time (TM) and Value-Added time (VA) are calculated and filled in the timeline summary, as shown in Fig. 8c. VA is the sum of the duration of each of the value-added activities in the activity chain. TM is the sum of each duration of every activity in the activity chain, including value-added and non-value-added activities.

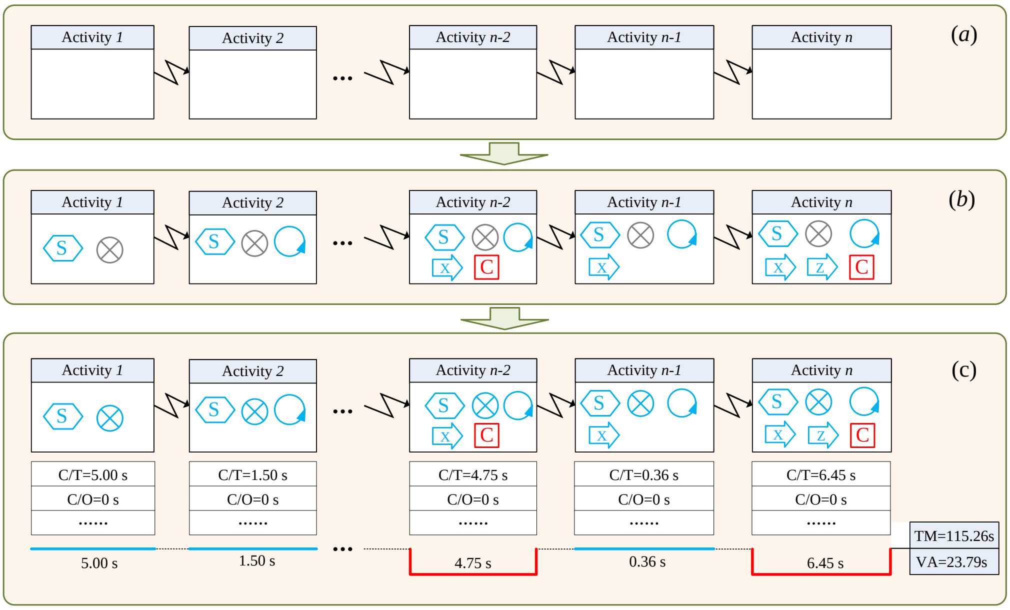


Fig. 8. Establishing procedure of a TVSM of machining process.

Taking activity *n*-2 as an example, the corresponding Therbligs of activity *n*-2 are Therblig-SO ⟨S⟩, -L ⊗, -SR ○, -XF ⟨X⟩ and -MC $\boxed{C}$. Therefore, Therblig-SO ⟨S⟩, -L ⊗, -SR ○, -XF ⟨X⟩ and -MC $\boxed{C}$ are embedded into activity *n*-2. The value-added Therblig (-MC $\boxed{C}$) is described in red, while other non-value-added Therbligs are described in blue. As this activity contains value-added Therblig (-MC $\boxed{C}$), the activity *n*-2 is therefore a typical VAA. According to Table 1, the C/T of activity *n*-2 is 4.75 s, which is filled into the corresponding data box. Due to the coherence of activities when the machining process is started, the C/O of activity *n*-2 is therefore 0 s. In addition, the timeline of is drawn under the data box of activity *n*-2. The timeline of activity *n*-2 is drawn in red since this activity is a VAA, as mentioned above. Then, the C/T value (4.75 s) of activity *n*-2 is labeled on the timeline. The components and information of the other activities can be established following the same approach. The TM and VA can be calculated and entered into the timeline summary according to the timeline of each activity. Finally, the TVSM of the entire machining process is established. Because the activities and corresponding Therbligs in Table 1 were extracted from the actual machining process, the established

TVSM is considered a Current-State-Map (CSM).

3.2.4. Analysis of the time and energy efficiency of the CSM

A typical CSM of TVSM is shown in Fig. 8. The CSM can highlight the sources of energy waste in Therbligs and activities and help us find the energy saving opportunities. Based on the CSM and the established power models of Therbligs [74,85,86], three types of efficiencies can be calculated to evaluate time and energy consumed throughout the value stream, including the time efficiency of value-added activity η_{VA}, the energy efficiency of value-added activity η_{VAA} and the energy efficiency of value-added Therblig η_{VAT}.

Equation (1) calculates the time efficiency of value-added activity η_{VA}, which is defined as the ratio of the value-added activity time and total machining time, which is expressed as:

$$\eta_{VA} = VA/TM = \sum_{i=1}^{N_{VAA}} t_{VAAi} \Bigg/ \sum_{j=1}^{N_A} t_{Aj} \tag{1}$$

where, VA is the value-added activity time during the machining process, s; TM is the total time of machining process, s; t_{VAAi} is the duration of i^{th} value-added activity, s; N_{VAA} is the number of value-added activities; t_{Aj} is the duration of the j^{th} activity, s; N_A is the total number of activities (including value-added and non-value added).

Equation (2) calculates the energy efficiency of value added activity η_{VAA}, which is defined as the ratio of the value-added activity's energy and the total machining energy, which is calculated as:

$$\eta_{VAA} = E_{VAA}/E_{TM} = \sum_{i=1}^{N_{VAA}} e_{VAAi} \Bigg/ \sum_{j=1}^{N_A} e_{Aj} \tag{2}$$

where, E_{VAA} is the energy demand of the value-added activities, J; E_{TM} is the total energy demand of the machining process, J; e_{VAAi} is the energy demand of the i^{th} value-added activity, J; e_{Aj} is the energy demand of the j^{th} activity, J.

Equation (3) is the energy efficiency of value-added Therblig η_{VAT} ,which is defined as the ratio of value-added Therblig energy and the total machining energy, which is computed as:

$$\eta_{VAT} = E_{VAT}/E_{TM} == \sum_{i=1}^{N_{VAT}} e_{VATi} \Bigg/ \sum_{j=1}^{N_A} e_{Aj} \tag{3}$$

where, E_{VAT} is the energy demand of value-added Therblig, J; E_{TM} is the total energy demand of the machining process, J; e_{VATi} is the energy demand of the i^{th} value-added Therblig, J.

3.2.5. Establishing the FSM of TVSM

The evaluations of η_{VA}, η_{VAA}, and η_{VAT} of a CSM can show the level of time and energy efficiency and reveal the energy-saving potential in the machining process. These three efficiencies provide objective evaluation indicators for the energy performance of a machining process. It is necessary to note that the point of getting lean is not “mapping”, which is just a technique. The important goal is implementing a value-adding flow. To create this flow we need a "vision" of the flow. Mapping helps us see and focus on flow with a vision of an ideal, or at least improved, state [82]. TVSM is aimed to highlight the sources of energy waste and eliminate them by implementing a future state value stream. The future state value stream is illustrated in the form of a Future-State-Map (FSM), as shown in Fig. 9.

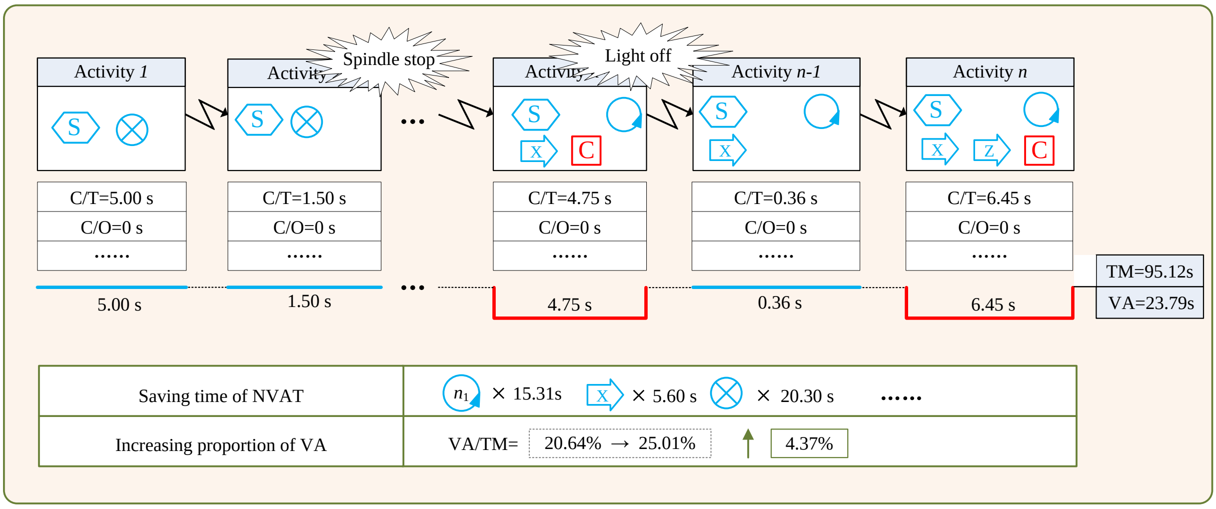


Fig. 9. Therblig-embedded value stream mapping (Future-State-Map).

The CSM of TVSM is the foundation of the establishment of FSM. VATs (marked in red in the CSM) create value, and the proportion of this type of Therblig should be increased via extending the duration or increasing the power of VATs. N-NVATs (marked in blue in the CSM) do not create value but are necessary, the execution time and power of this type of Therblig should be decreased. U-NVATs (marked in blue in the CSM) do not create value and are unnecessary, which is typical waste and should be eliminated. Some Therbligs (e.g., -SO ⟨S⟩, -CFS ≋, etc.) may be N-NVAT in one activity while U-NVAT in another activity. Hence, the N-NVATs and U-NVATs need to be evaluated according the actual machining requirements. Similarly, waste activities can be eliminated or optimized at the activity level. With the help of the CSM of Therblig-embedded VSM, the sources of energy wastes are easily identified. Consequently, the FSM can be built via eliminating the energy wastes (see Fig. 9), by removing the U-NVATs and reducing the time and power of N-NVATs, etc.

3.2.6. Comparison between FSM and CSM

Based on the established FSM and CSM, the time and energy comparison between FSM and CSM can be performed. Taking one specific activity as an example (see Fig. 10), the duration of an activity in the CSM can be obtained according to the activity extraction results in Table 1. Supposing the obtained duration is t_1, then duration of each Therblig in this activity is also t_1. In addition, the power of each Therblig in this activity can be calculated based on the power models of Therbligs. Consequently, the energy demand of each Therblig in this activity can be learned. Similarly, the duration and energy demand of each Therblig of this activity in the FSM can also be gained. As a result, the savings of duration and energy of each Therblig can be obtained, as shown in Fig. 10.

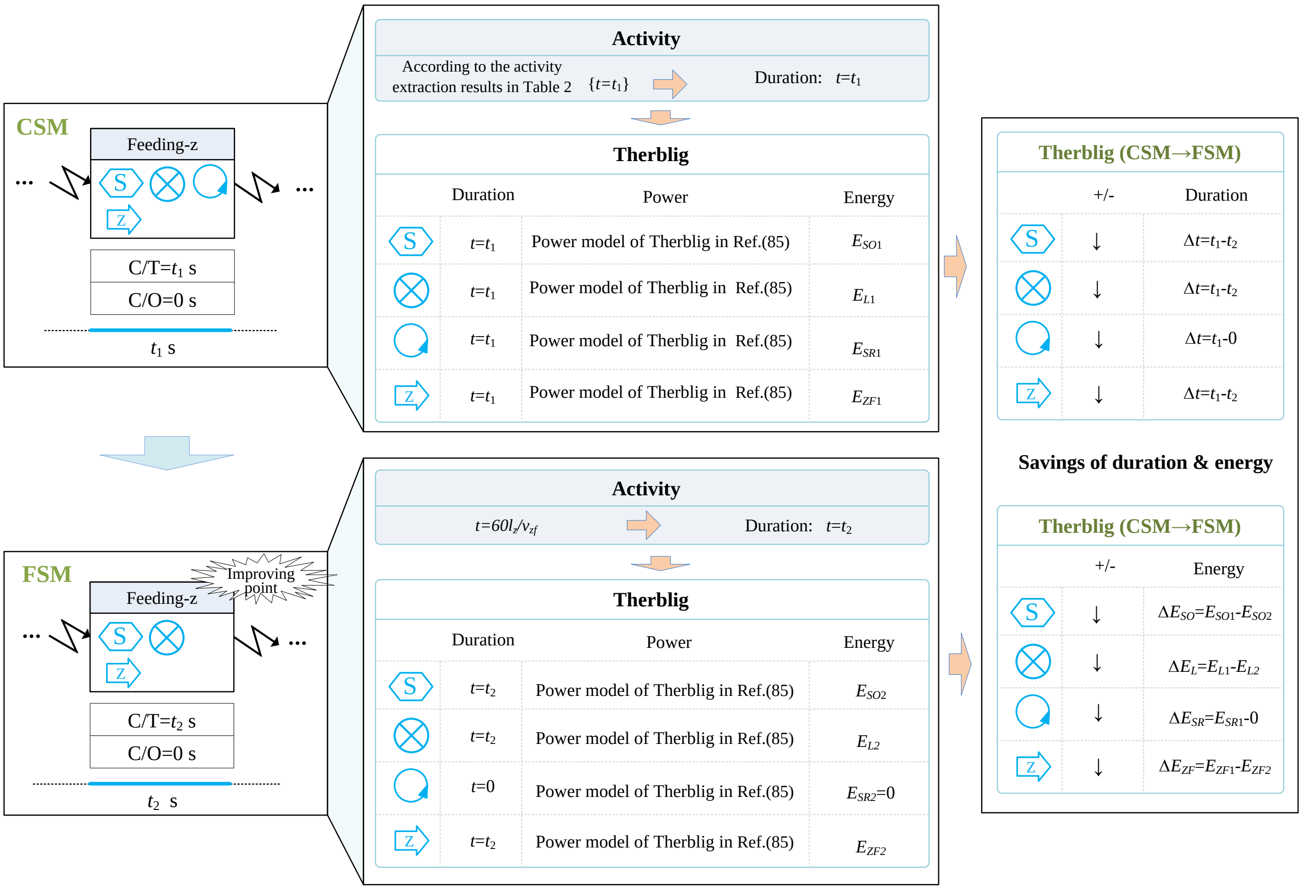


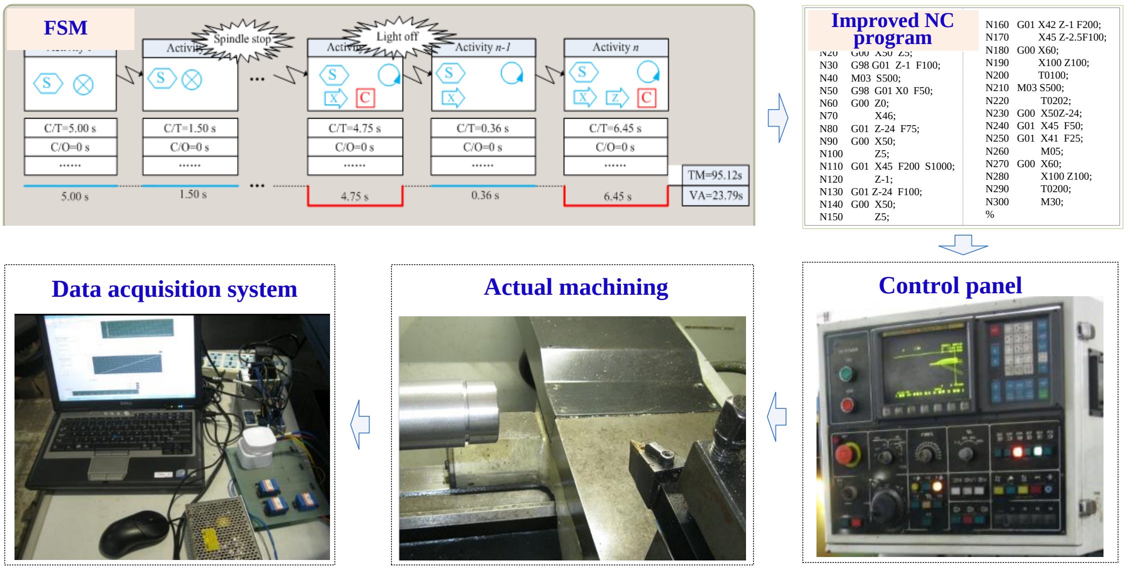
Fig. 10. Comparison between FSM and CSM.

Once the duration and energy demand of each Therblig in the activity have been obtained, the duration and energy demand of each activity can be easily be determined. Then the total duration and total energy demand of the machining process can be obtained by summing up the duration and energy demand of each activity.

Consequently, the time efficiency of value-added activity (η_{VA}), the energy efficiency of value-added activity(η_{VAA}) and the energy efficiency of value-added Therblig (η_{VAT}) can be calculated under the conditions of the FSM and CSM.

3.2.7. Implementing the FSM

Establishing the FSM is not the ultimate goal; implementing the FSM to realize energy savings and improve efficiency should be the focus. As shown in Fig. 11, the initial NC program should be modified by considering all the areas that can be improved in the FSM to obtain the improved NC program. Then the improved NC program will be loaded into the machine tool through the control panel and the actual machining process will be performed, and the power and energy information are measured simultaneously for the verification of energy saving and efficiency improvement results.



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N20   G00  X50  Z5;
N30   G98 G01  Z-1  F100;
N40   M03  S500;
N50   G98  G01 X0  F50;
N60   G00  Z0;
N70          X46;
N80   G01  Z-24  F75;
N90   G00  X50;
N100         Z5;
N110  G01  X45  F200  S1000;
N120         Z-1;
N130  G01 Z-24  F100;
N140  G00  X50;
N150         Z5;
N160  G01 X42 Z-1 F200;
N170        X45 Z-2.5F100;
N180  G00 X60;
N190        X100 Z100;
N200        T0100;
N210  M03 S500;
N220         T0202;
N230  G00  X50Z-24;
N240  G01  X45  F50;
N250  G01  X41  F25;
N260         M05;
N270  G00  X60;
N280         X100 Z100;
N290         T0200;
N300         M30;
%
```

Fig. 11. Implementation of the FSM.

4. Case study

To show the validity of the proposed approach, an analysis of the machining processes of a typical workpiece was performed. In order to demonstrate the case more clearly, this section is divided into eight subparts, as shown in Fig. 12.

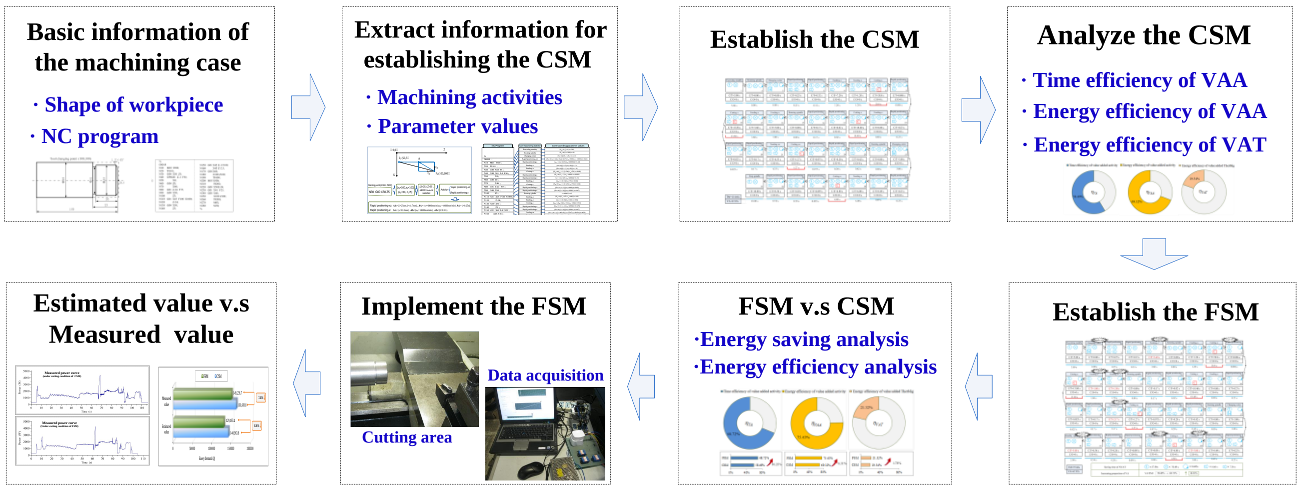
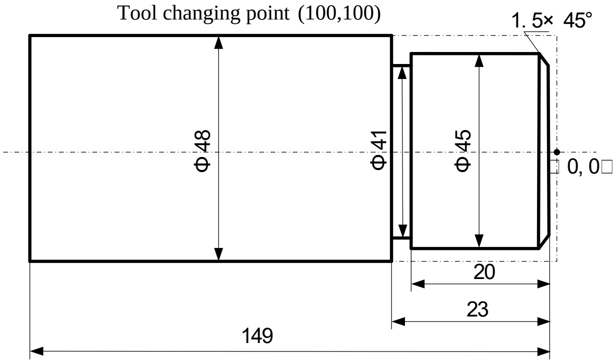


Fig. 12. Eight subparts of the machining case study.

4.1. Basic information about the machining case

The blank (Φ = 48mm, L = 150mm, material = C45 Steel) was machined to shape the test workpiece through five cutting processes: face turning, rough external turning, fine external turning, chamfering and grooving. The workpiece and corresponding NC program are shown in Fig. 13. The machining case was conducted on a CK6153*i* CNC lathe, which was manufactured by Jinan First Machine Tool Group Co., Ltd. of China.



```
%
O0018
N10    M03  S500;
N20    T0101;
N30    G00  X50  Z5;
N40    G98G01  Z-1  F50;
N50            X0;
N60    G00  Z0;
N70            X46;
N80    G01  Z-24  F75;
N90    G00  X50;
N100           Z5;
N110   G01  X45  F100  S1000;
N120           Z-24;
N130   G00  X50;
N140           Z5;
```

```
N150   G01 X42 Z-1 F100;
N160           X45 Z-2.5;
N170   G00 X60;
N180           X100 Z100;
N190           T0100;
N200   M03 S500;
N210           T0202;
N220   G00  X50Z-24;
N230   G01  X41  F25;
N240   G00  X60;
N250           X100 Z100;
N260           T0200;
N270           M05;
N280           M30;
%
```

Fig. 13. Test workpiece and NC program.

4.2. Extracting information for establishing the CSM

According to the activity extraction method and mapping between activities and Therbligs, as researched in our previous literature [85, 86], thirty-five activities can be extracted from the machining process for the above workpiece. The extraction process is briefly shown in Fig. 14, for more detailed information about the extracting processes, refer to reference [85, 86]. The extracted activities and corresponding Therbligs of the machining case are listed in Table 2.

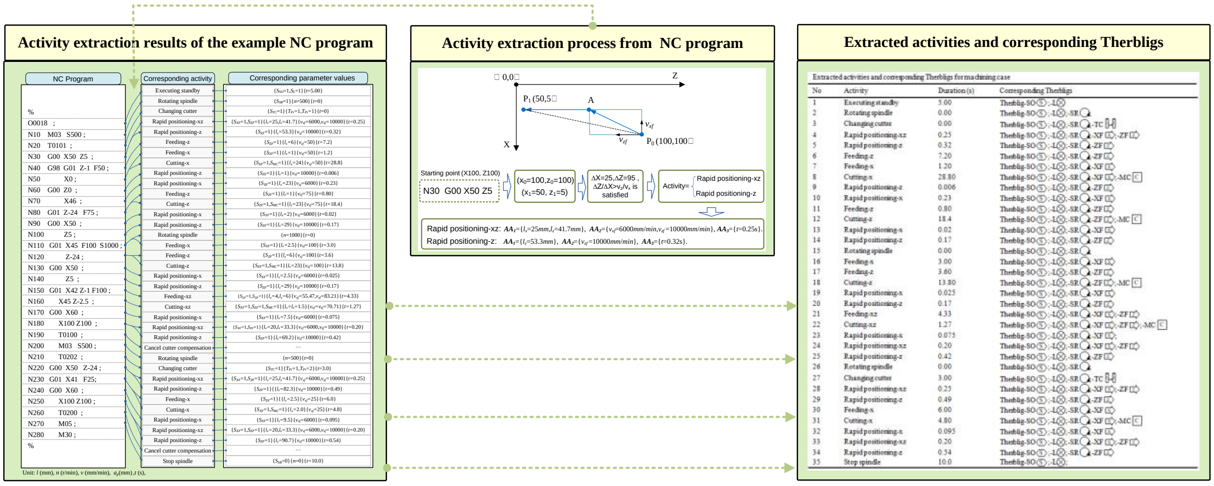


Fig. 14. Extraction process of the machining activities and corresponding Therbligs.

Table 2
Extracted activities and corresponding Therbligs for the machining case.

No	Activity	Duration (s)	Corresponding Therbligs
1	Executing standby	5.00	Therblig-SO⟨S⟩;-L⊗
2	Rotating spindle	0.00	Therblig-SO⟨S⟩;-L⊗;-SR◔;
3	Changing cutter	0.00	Therblig-SO⟨S⟩;-L⊗;-SR◔;-TC 1→2
4	Rapid positioning-xz	0.25	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;-ZF Z⇨
5	Rapid positioning-z	0.32	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
6	Feeding-z	7.20	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
7	Feeding-x	1.20	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨
8	Cutting-x	28.80	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;-MC $\boxed{C}$
9	Rapid positioning-z	0.006	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
10	Rapid positioning-x	0.23	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨
11	Feeding-z	0.80	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
12	Cutting-z	18.4	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨;-MC $\boxed{C}$
13	Rapid positioning-x	0.02	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨
14	Rapid positioning-z	0.17	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
15	Rotating spindle	0.00	Therblig-SO⟨S⟩;-L⊗;-SR◔;
16	Feeding-x	3.00	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨
17	Feeding-z	3.60	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
18	Cutting-z	13.80	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨;-MC $\boxed{C}$
19	Rapid positioning-x	0.025	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨
20	Rapid positioning-z	0.17	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
21	Feeding-xz	4.33	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;-ZF Z⇨
22	Cutting-xz	1.27	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;-ZF Z⇨;-MC $\boxed{C}$
23	Rapid positioning-x	0.075	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;
24	Rapid positioning-xz	0.20	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;-ZF Z⇨
25	Rapid positioning-z	0.42	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
26	Rotating spindle	0.00	Therblig-SO⟨S⟩;-L⊗;-SR◔;
27	Changing cutter	3.00	Therblig-SO⟨S⟩;-L⊗;-SR◔;-TC 1→2
28	Rapid positioning-xz	0.25	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;-ZF Z⇨
29	Rapid positioning-z	0.49	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
30	Feeding-x	6.00	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨
31	Cutting-x	4.80	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;-MC $\boxed{C}$
32	Rapid positioning-x	0.095	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨
33	Rapid positioning-xz	0.20	Therblig-SO⟨S⟩;-L⊗;-SR◔;-XF X⇨;-ZF Z⇨
34	Rapid positioning-z	0.54	Therblig-SO⟨S⟩;-L⊗;-SR◔;-ZF Z⇨
35	Stop spindle	10.0	Therblig-SO⟨S⟩;-L⊗;

4.3. Establishing the CSM

According to Table 2 and the establishment steps of TVSM given in section3.2.3, the CSM of TVSM of the machining case can be established. Taking activity1 as an example, the corresponding Therbligs of are Therblig-SO ⟨S⟩ and -L ⊗. Therefore, Therblig-SO ⟨S⟩ and -L ⊗ are embedded into the activity1 in blue (NVAT). Since no value-added Therbligs are contained in activity1, it is identified as a NVAA. According to Table 2, the C/T of activity1 is 5.00 s, which is filled into the corresponding data box. In addition, the timeline is drawn under the data box of activity1. The timeline of activity1 is drawn in blue since this activity is a NVAA, and then, the C/T value (5.00s) is labeled on the corresponding timeline. Following the same approach, the date for the remaining thirty-four activities can be drawn and the TM and VA of the value stream can be summarized. Finally, the CSM of TVSM of the machining case is established, as shown in Fig. 15.

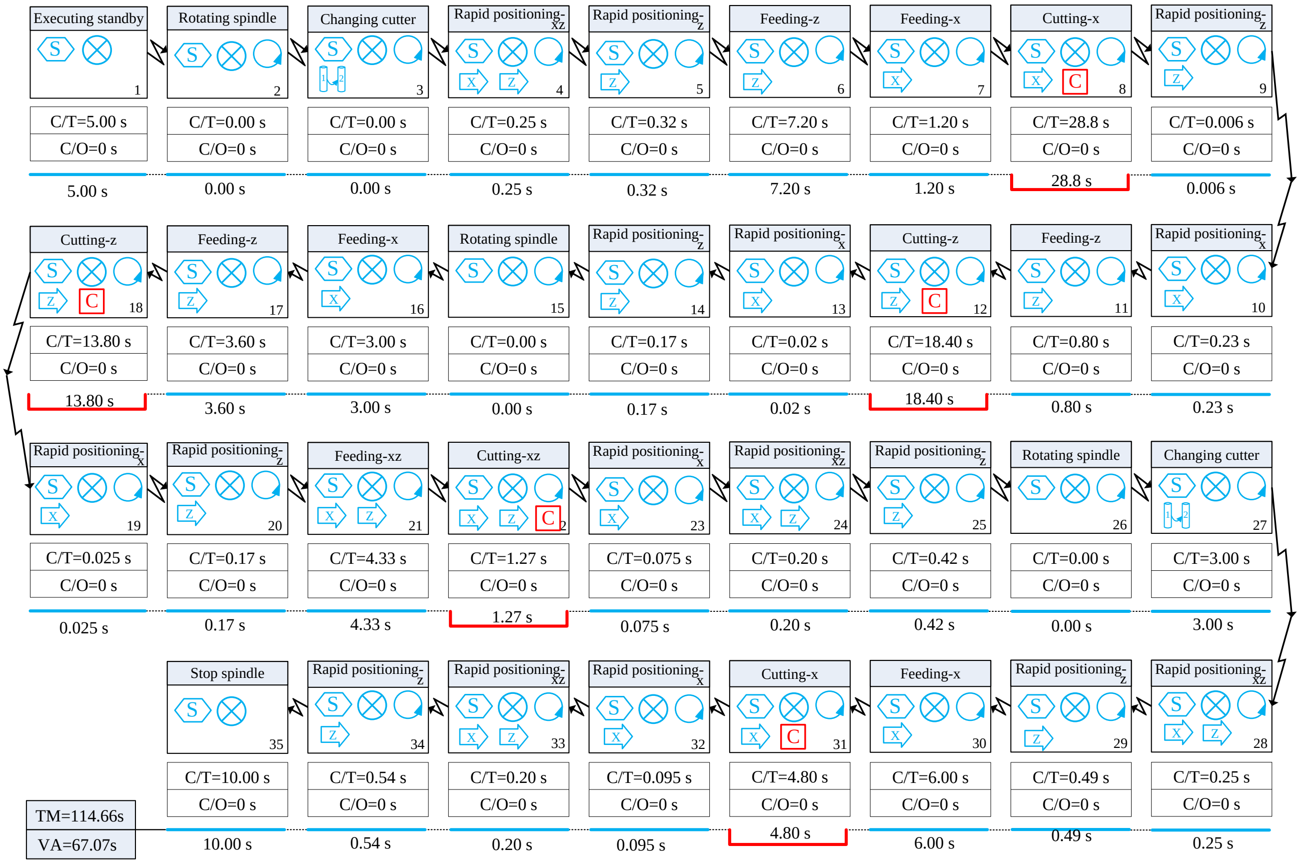


Fig. 15. Current-State-Map of TVSM of the machining case.

4.4. Analyzing the CSM

Based on the above CSM, it is obvious that there are only five value-added activities, activity 8, 12, 18, 22, and 31, from a lean energy perspective. Each VAA contains one value-added Therblig, which is depicted in red. According to the CSM, the value-added time (VA) and total machining time (TM) of the machining case are 67.07

s and 114.66 s, respectively. Hence, the time efficiency of the VAA can be evaluated (58.49%) based on Equation (1). In addition, cycle time and Therbligs of each activity have been shown in the CSM. In conjunction with the Therblig power models established in our previous work [85], the energy demand of each Therblig or activity and that of the total machining process can be calculated. Specifically, the calculated energy demands of the five value-added activities and total machining process are 32106.24 J, 28711.36 J, 26767.86 J, 2558.42 J, 7293.60 J and 140963.77 J, respectively. Therefore, the energy demand of the value-added activities can be obtained (E_{VAA} =97437.48 J). The energy efficiency of the value-added activity can be evaluated (69.12%) based on Equation (2). Similarly, the energy efficiency of the value-added Therblig can be calculated based on Equation (3). The time and energy efficiency (η_{VA} , η_{VAA} and η_{VAT}) of the machining case are summarized in Fig. 16.

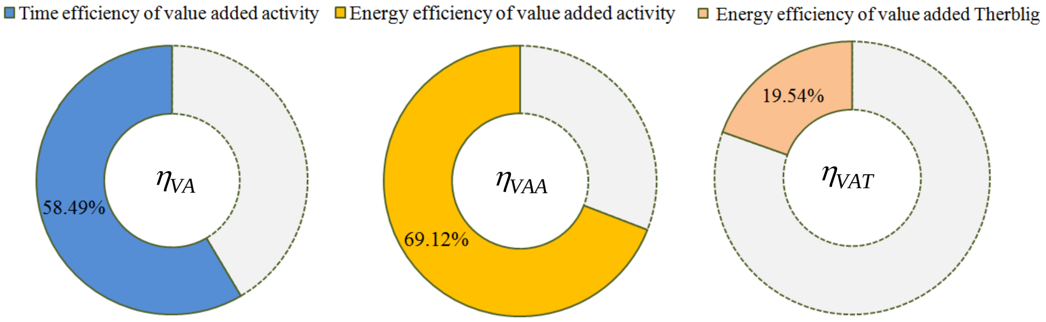


Fig. 16. Time and energy efficiency (η_{VA} , η_{VAA} and η_{VAT}) of the machining case (CSM).

4.5. Establishing the FSM

As the time and energy efficiency of VAA are both less than 70%, some room for improvement exists. When it comes to value-added Therblig, the energy efficiency is only 19.54% and the potential to improve is significant. Even during the value-added activity, non-value-added Therbligs still exist and account for a large proportion of the energy demand. The TVSM method obviously provides a detailed analysis and exposes improvement opportunities for lean energy machining. In order to improve the time and energy efficiency of the machining process, several energy efficiency improving strategies can be adopted: 1) eliminate waste Therblig/activity; 2) decrease the duration of NVAT and NVAA; 3) decrease the power of NVAT and NVAA.

For instance, the first material-cutting Therblig (VAT) was not executed until activity8, therefore early execution of Therblig-SR is a waste. Then the execution time of activity-2 "spindle rotating" in the CSM can be postponed and Therblig-SR ↻ (NVAT) in activities 2-6 in the CSM can be eliminated, as shown in the FSM of TVSM (see Fig. 17). The executing time of Therblig-SR ↻ can be reduced to 7.77s by adopting the above approach. The spindle speed was 500 r/min before the improvement was adopted. According to the Therblig power models established in [85], the power of Therblig-SR ↻ can be calculated as $P_{SR}=1.09n+41.12=1.09\times500+41.12=586.12$ W. Consequently, the energy demand can be reduced 4554.15 J. Moreover, for some feeding activities, feeding speed can be increased to decrease the feeding time. For example, duration of activity-6 "feeding-z" in the CSM (corresponding activity-5 in the FSM) is 7.20s. The feeding time can be decreased into 3.60 s via increasing the feeding speed from 50 to 100 mm/min. Consequently, the executing time of Therblig-SO ⟨S⟩, -L ⊗ and -ZF Z⇨ and activity-6 (corresponding activity-5 in the FSM) are all reduced, as shown in Fig. 19. Although the increased feeding speed makes the power of Therblig-ZF Z⇨ increase, the reduction of executing time plays a major role in the change of energy demand. The power of Therblig-SO ⟨S⟩ and -L⊗ for the researched CK6153*i* lathe are 312.1 W and 20 W, respectively [85]. Moreover, the power of Therblig-ZF Z⇨ at the speed of 50 and 100 mm/min can be calculated (2.0 W and 3.5 W) according to the formula $P_{ZF}=0.49+0.03v_{zf}+2.32\times10^{-6}v_{zf}^{2}$ [85]. Therefore, the energy reduction of Therblig-SO ⟨S⟩ and -L⊗ can be obtained (312.1×3.6=1123.56J; 20×3.6=72 J). Additionally, the energy reduction of Therblig-ZF Z⇨ can be calculated(2.0×7.2-3.5×3.6=1.8 J). Then, the total energy reduction of activity-6 "feeding-z" (activity-5 in the FSM) can be obtained (1123.56+72+1.8=1197.36J). Following the same approach, some other areas for improvement can be identified and marked in the FSM of TVSM, as shown in Fig. 17.

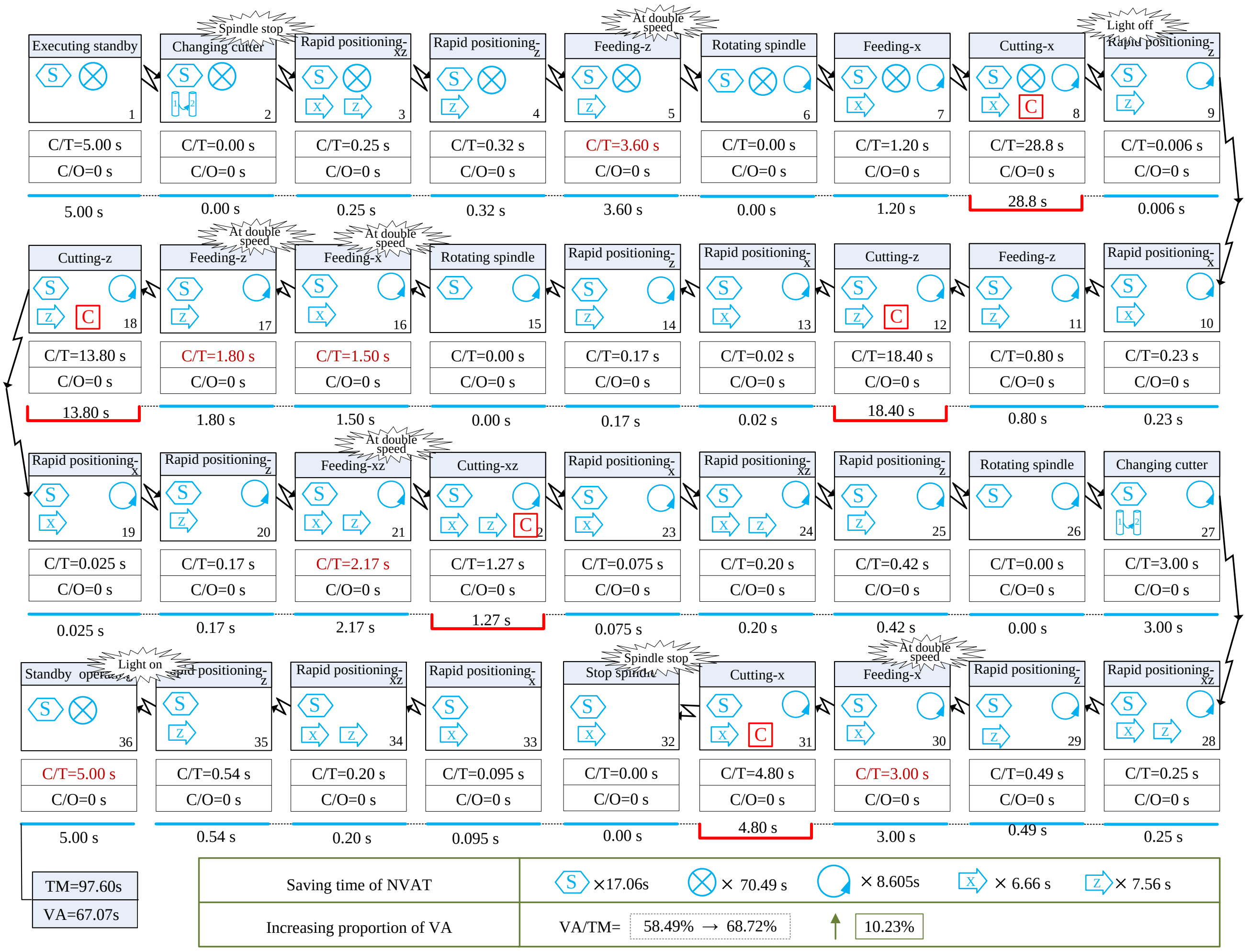
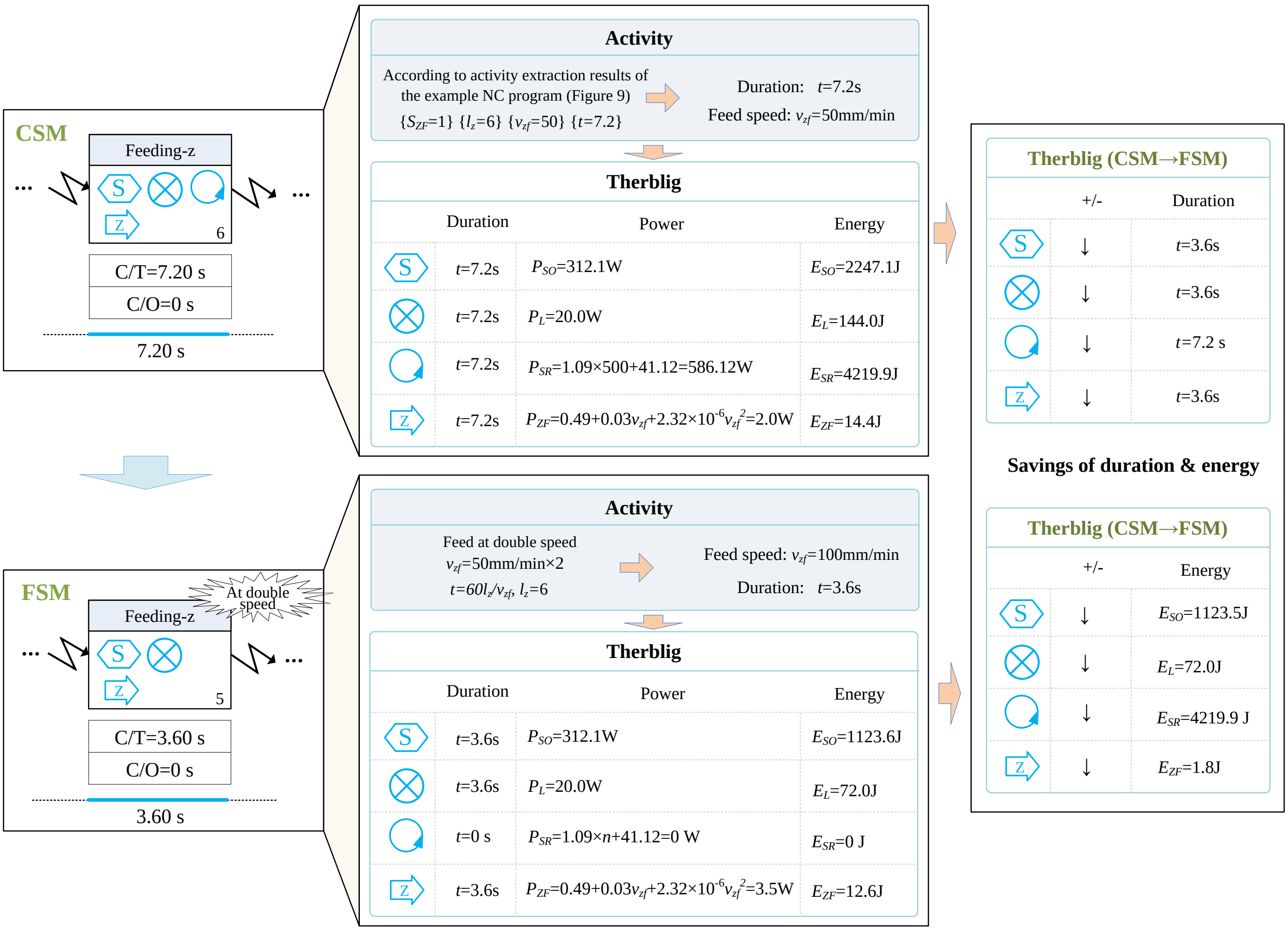


Fig. 17. Future-State-Map of TVSM of the machining case.

4.6. FSM v.s CSM

Based on the established CSM and FSM, the savings of duration and energy of Therbligs can be calculated. Fig. 18 shows the calculation process of savings of duration and energy for one activity. Following the same method, these savings for all the activities can be obtained. Then, the total time and energy savings of the machining process can be obtained by summing up the savings of each activity, as shown in Fig. 19.



Activity

According to activity extraction results of the example NC program (Figure 9)
$\{S_{ZF}=1\}$ $\{l_z=6\}$ $\{v_{zf}=50\}$ $\{t=7.2\}$

Duration: t=7.2s
Feed speed: v_{zf}=50mm/min

Therblig

	Duration	Power	Energy
S	t=7.2s	P_{SO}=312.1W	E_{SO}=2247.1J
⊗	t=7.2s	P_L=20.0W	E_L=144.0J
◯	t=7.2s	P_{SR}=1.09×500+41.12=586.12W	E_{SR}=4219.9J
Z	t=7.2s	$P_{ZF}=0.49+0.03v_{zf}+2.32\times10^{-6}v_{zf}^2$=2.0W	E_{ZF}=14.4J

Activity

Feed at double speed
v_{zf}=50mm/min×2
$t=60l_z/v_{zf}$, l_z=6

Feed speed: v_{zf}=100mm/min
Duration: t=3.6s

Therblig

	Duration	Power	Energy
S	t=3.6s	P_{SO}=312.1W	E_{SO}=1123.6J
⊗	t=3.6s	P_L=20.0W	E_L=72.0J
◯	t=0 s	P_{SR}=1.09×n+41.12=0 W	E_{SR}=0 J
Z	t=3.6s	$P_{ZF}=0.49+0.03v_{zf}+2.32\times10^{-6}v_{zf}^2$=3.5W	E_{ZF}=12.6J

Therblig (CSM→FSM)

	+/-	Duration
S	↓	t=3.6s
⊗	↓	t=3.6s
◯	↓	t=7.2 s
Z	↓	t=3.6s

Savings of duration & energy

Therblig (CSM→FSM)

	+/-	Energy
S	↓	E_{SO}=1123.5J
⊗	↓	E_L=72.0J
◯	↓	E_{SR}=4219.9 J
Z	↓	E_{ZF}=1.8J

Fig. 18. Calculation of savings of duration and energy for one activity.

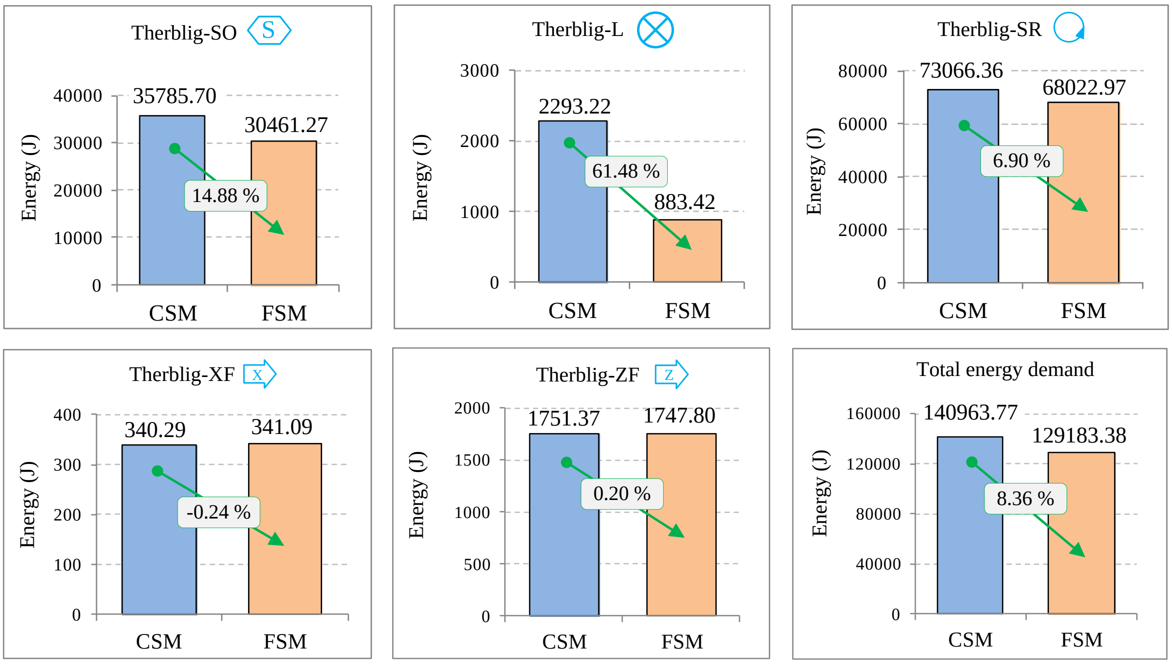


Fig. 19. Improvement results of energy demands of Therbligs and the machining process.

According to Fig. 19, the reduction of the energy demands of Therblig-SO S, -L⊗, -SR ◯ are remarkable. The reasons are listed as follows: 1) for Therblig-SO ⟨S⟩, the power (312.1 W) and reduced time (17.06 s) are both significant; 2). for Therblig-L ⊗, although the power consumed(20 W) is not large, the energy saved is also significant due to the large reduction in duration of the activity (70.49 s); and 3) for Therblig-SR ◯, to maintain the spindle rotating at a high speed, usually more than 500 r/min, the power consumed by this Therblig is relatively high (586.1 W at 500 r/min). Therefore, considerable energy can be saved with this type of Therblig in conjunction with the reduced duration (8.605 s). The reduction of energy of Therblig-XF X⇨ and -ZF Z⇨ are not significant. Because the reduced durations are obtained by increasing the feeding power. The tradeoff between the reduced duration and increased power makes the energy savings of Therblig-XF X⇨ and -ZF Z⇨ are negligible. The energy demand of Therblig-XF X⇨ is even increased by 0.24% due to its increased power. However, the energy savings of Therblig-SO ⟨S⟩, -L ⊗ , -SR ◯ play a major role in the energy changes in the machining case. Consequently, the total energy demand of the machining process can be reduced by 8.36% with implementing the FSM, as shown in Fig. 19.

The time and energy efficiency (η_{VA}, η_{VAA} and η_{VAT}) of the machining case can also be improved by implementing the FSM, as shown in Fig. 20. It can be seen that η_{VA}, η_{VAA} and η_{VAT} are all improved to a certain extent. The adopted strategies either shorten the duration or reduce the power of the NVATs and NVAAs, and eliminate waste NVATs and NVAAs. Meanwhile, this improvement is achieved without changing the value-added time and parameters for actually cutting material; the machining quality is therefore not affected. This is consistent with the aim of lean energy machining; machining more material with less energy without lowering the machining quality.

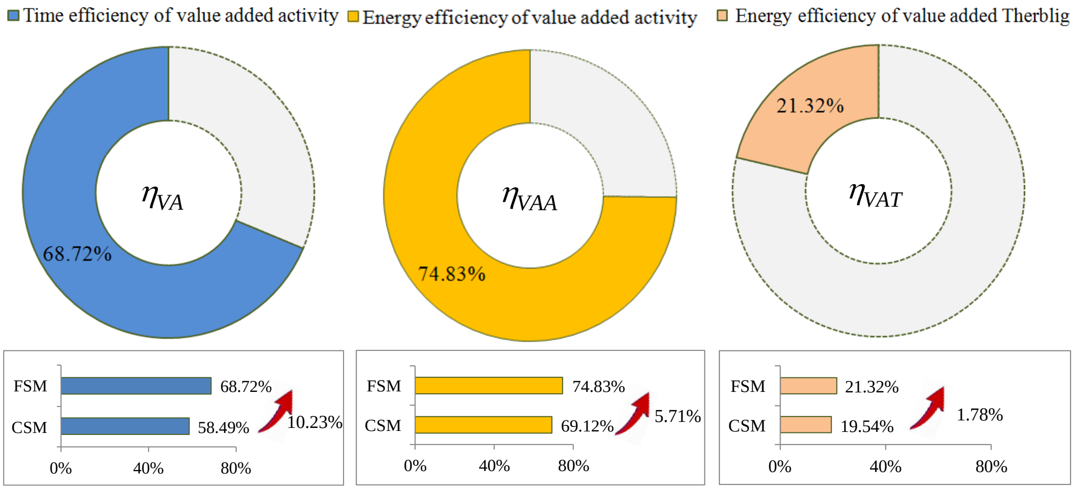


Fig. 20. Time and energy efficiency (η_{VA}, η_{VAA} and η_{VAT}) of the machining case (FSM).

4.7. Implementing the FSM

Based on the established FSM (see Fig. 17), all the improvement areas were reflected in the improved NC program. Then the machining case was performed again under the FSM conditions, as shown in Fig. 21. Simultaneously, the power and energy data during the machining processes were collected with the data acquisition system shown in Fig. 21*b*. For detailed information about the data acquisition system, refer to reference [74,85]. Consequently, the measured power curve under the FSM conditions was obtained, as depicted in Fig. 21*d*. Similarly, the measured power curve under the CSM conditions was obtained, as shown in Fig. 21*c*.

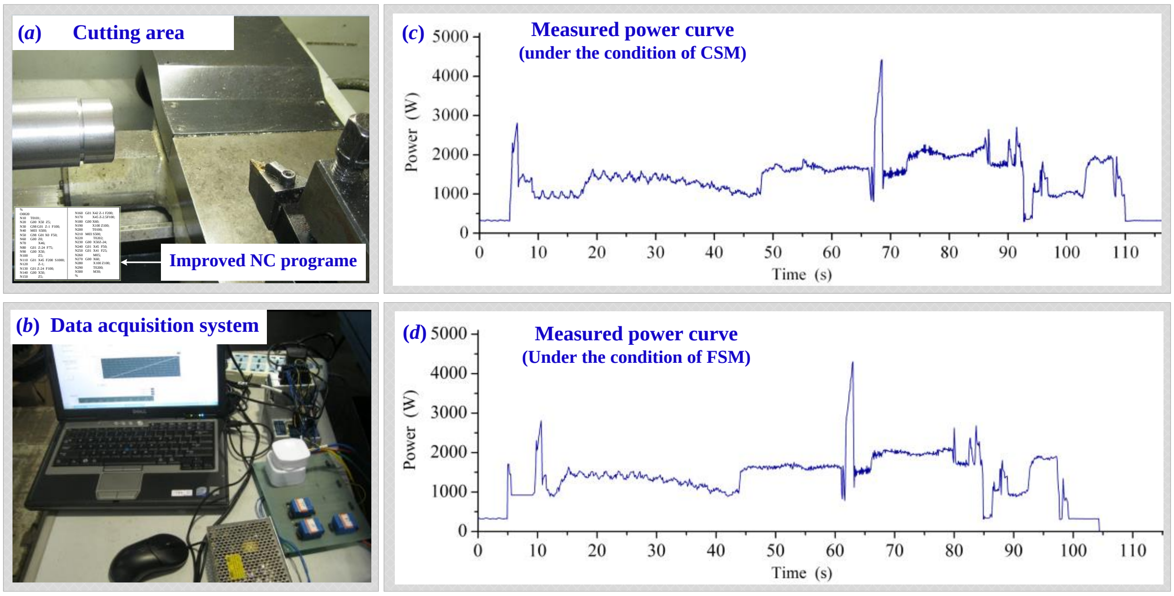


Fig. 21. Relevant information during implementing the FSM.

5. Results and discussion

The energy consumption and efficiency under the CSM and FSM conditions have been estimated in section 4.6. In addition, the power and energy information under the CSM and FSM conditions have been measured according to section 4.7. Next the comparisons of the estimated values verse the measured values have been conducted to show the validity of the proposed method. As shown in Fig. 22, we estimated the total energy demand of the machining case would be reduced by 8.36% by implementing the FSM. The measured results showed that the actual reduction of the total energy demand was 7.65%. The measured result shows that the energy savings for machining one part is 12364.3 J by implementing the approach in this paper. Consequently, the total energy saving could reach up to $1.03*10^5$ kWh for one year, assuming 100 machine tools with 1000parts manufactured per machine per day for 300days per year.

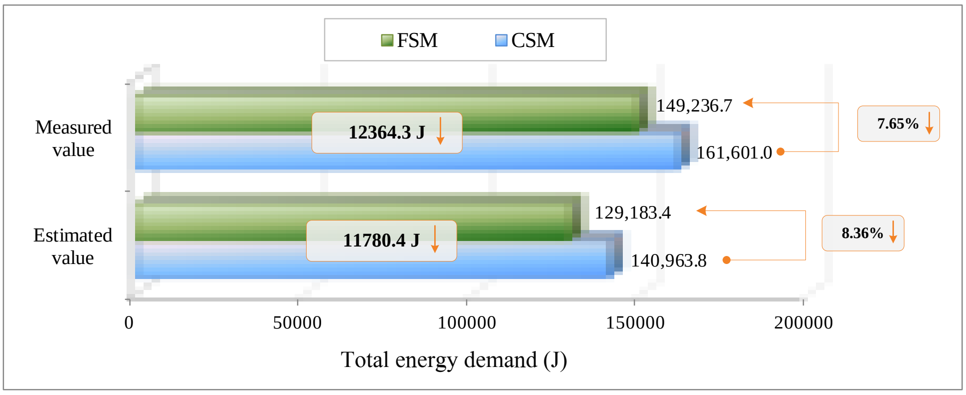


Fig. 22. Measured v.s. estimated total energy demand.

According to Fig. 20, the time efficiency of the value-added activity (η_{VA}) was predicted to be improved by 10.23% via implementing the FSM. As illustrated in Fig. 23a, the actual measured time efficiency of the value-added activity was increased by 8.12%. Similarly, the energy efficiency of the value-added activity (η_{VAA}) and the value-added Therblig (η_{VAT}) were predicted to be increased by 5.71% and 1.78%, respectively. The measured increased percentage of these two efficiencies were 4.95% and 1.58%, as shown in Fig. 23b and Fig. 23c.

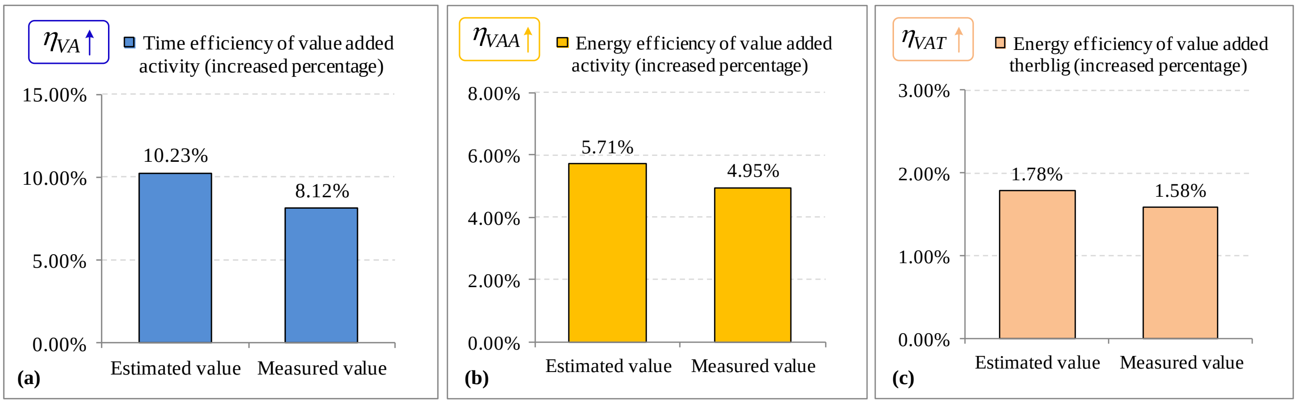


Fig. 23. Measured v.s. estimated time and energy efficiency increases.

The differences between the estimated and measured values are small, generally less than 5%. Moreover, the measured results showed that the time and energy efficiencies of the machining case were significantly improved by implementing the FSM, with η_{VA} improved by 8.12%, η_{VAA} improved by 4.95%, and η_{VAT} improved by 1.58%, which shows the effectiveness of the proposed method.

The Chinese premier indicated that the energy consumption and CO_2 emissions per unit of GDP in China should be decreased by 15% and 18% respectively, before 2020 [87]. The manufacturing industry, as one the major sources of energy consumption in China, plays an important role in achieving this goal of national energy saving and emission reduction. To effectively manage and control the energy consumption in manufacturing, both the industry and the government are trying to establish the energy consumption allowance for workpieces in the manufacturing industry [88,89]. The establishment of an energy consumption allowance will bring a new challenge to manufacturing enterprises. The energy consumption of any product should meet or be even lower than the established allowance. The approach in this paper is a promising method to help manufacturing enterprise achieve this goal. This approach can support the designers to create high energy efficiency machining processes during the planning stage. More specifically, there are two key recommendations for designers during the machining process planning stage: (1) as shown in Fig. 24, after the cutting tool fast approaching the workpiece, usually following two stages: air-cutting stage and material-cutting stage. Energy savings and efficiency improvement can be achieved through increasing the feeding speed of the air-cutting stage (E.g. stage ②→③ and stage ③→④), while not changing the feeding speed of material-cutting stage. The feeding speeds of these two sub-stages are usually designed to be the same and due to cutting constraints, this feeding speed cannot be fast enough, resulting in energy and efficiency wastes. The proposed method can help the designer determine the air-cutting stages and analyze the effect of feeding speed of the air-cutting stage on the total energy consumption. Finally, energy savings can be achieved by changing the feeding speeds of air-cutting stages.

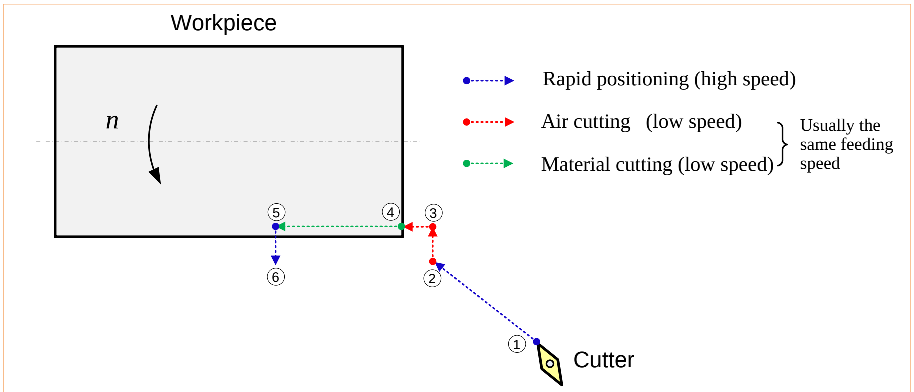


Fig. 24. Energy saving recommendations related to feeding speed.

(2) It is well known that energy savings can be achieved by reducing spindle idle time, however, to exactly determine the start and stop time of a spindle without affecting normal processing is not an easy task. With the help the TVSM tool, the designer can easily figure out the energy wastes of Therblig-spindle rotating and reduce them, which can achieve significant energy savings. As shown in Fig. 25, the energy consumption of stage ①→⑤ can be significantly reduced by adjusting the spindle start time and removing the energy wastes of Therblig-spindle rotating.

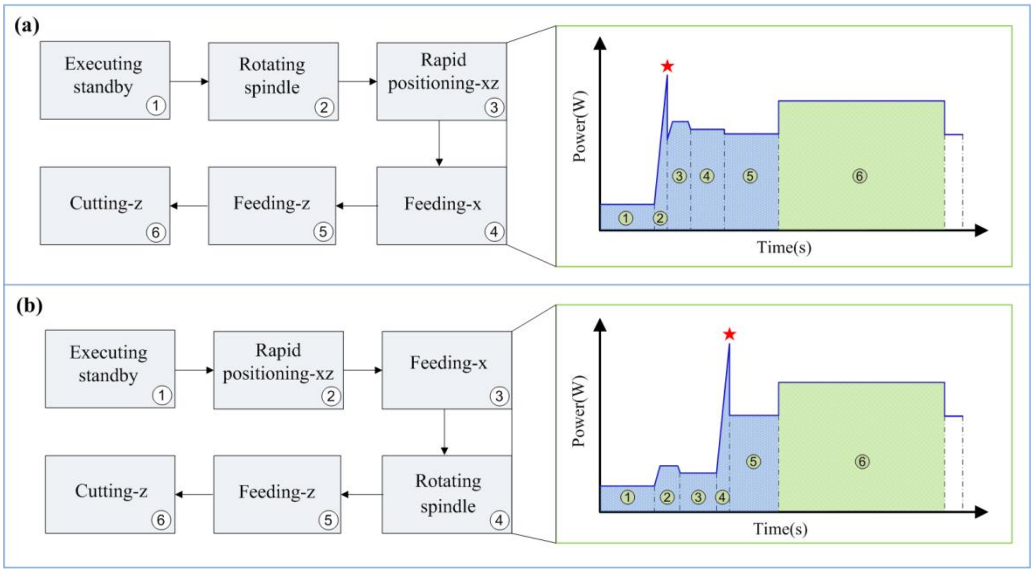


Fig. 25. Energy saving recommendations related to spindle rotation.

6. Conclusions

Realization of lean energy machining plays an important role in energy savings in the manufacturing industry. Although extensive studies have focused on optimizing the cutting parameters of the machining process, effective methods to accurately determine and reduce the energy wastes in NCA are still lacking. To bridge this gap, a novel TVSM method is proposed in this paper. The CSM of TVSM can be built according to the actual machining process by following the given steps. Based on the CSM, the non value-added activities and Therbligs can be easily determined, showing the opportunities for energy improvement. To achieve lean energy machining, the FSM can be established by eliminating non-valued-added activities and Therbligs, and shortening the time or lowering the power requirement of non-valued-added activities and Therbligs. By implementing the FSM, time and energy efficiencies can be improved in machining without decreasing the machining quality, which is consistent with the goal of lean energy machining. This method was validated by a typical machining case study; the results showed that the total energy demand was reduced by 7.65%, and the time efficiency of value-added activity was improved by 8.12% , and the energy efficiency of value-added activity and Therblig are raised by 4.95% and 1.58%, respectively.

The advantages of this method are: (1) due to not changing the cutting parameters, the machining quality is therefore not affected; (2) energy savings can be achieved without shortening the service life of the cutting tool; (3) the energy demand of NVAA occupies a large proportion of the total energy in the machining process and the energy saving potential is significant; (4) the approach can support designers to create a high energy efficiency machining process during the process planning stage. This paper mainly focused on evaluating the non-cutting activities and Therbligs, and reducing their energy demand. Optimization of cutting parameters, of course, is another important way for energy saving. In future work, better improvement results can be achieved by combining the method proposed in this paper with the optimization of cutting parameters.

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