Feature-based Approach in Product Design with Energy Efficiency Consideration

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Abstract. In this paper, a method to measure the energy efficiency and ecological footprint metrics of features is proposed for product design. First the energy consumption models of various manufacturing features, like cutting feature, welding feature, etc. are studied. Then, the total energy consumption of a product is modeled and estimated according to its features. Finally, feature chains that combined by several sequence features based on the producing operation orders are defined and analyzed to calculate global optimal solution. The corresponding assessment model is also proposed to estimate their energy efficiency and ecological footprint. Finally, an example is given to validate the proposed approach in the improvement of sustainability.

1.Introduction

As known all, the energy efficiency and environmentally friendliness of a product is very much depending on its usages, production and distribution only towards the end of the lifecycle. In fact, the energy efficiency and ecological footprint during usages, distribution and dispose stages have been studied for many authors [1-4]. Although the concept of features and the concept of design for manufacturing has been introduced for many decades, the influence of design on the energy consumption and carbon emission in the manufacturing stage have already been overlooked for many decades. From the process planning point of view, the allocation of machining stock to each machining process is very crucial in terms of energy consumption. Optimization of process plans and process parameters can effectively reduce the production energy [5-7]. For manufacturing companies, the abilities of manufacturing to respond changes in the market rely heavily on the process plan. The process plan is vitally important in providing a competitive edge to manufacturing [8]. The process sequence is fixed in the numerical control code on numerically controlled equipment. The operation instructions are described according to the relative motion between cutting tool and work piece. The drawback of using the fixed process sequence is the lack of activity to the unexpected events that occur at shop-floor level during executing phase [9].

To achieve the objective of energy efficiency in manufacturing stage, all available manufacturing ways should be evaluated in product design stage for optimum. To address this problem, in this paper, a manufacturing oriented product design approach is proposed. In the following sections, Section 2 describes the definition, classification and energy estimation modelling of features. Section 3 presents the energy estimation model of products. Section 4 is a case study, which is following by the section with the conclusions and indicates some directions for further study.
2. Classification and Energy Modeling of Features

From the viewpoint of product manufacturers, product features can be classified as cutting, welding and forming operations, etc. In some cases, these generation approaches are alternative if the requirements and constraints could be guaranteed, but their required energies are mostly different. To help to select adaptive features, techniques for the estimation of energy consumption and environmental impact of these features should be studied. Although the cutting feature and welding feature are only covered in this discussion the technique can similarly be transferred to other types of features.

Cutting features are generated by machine tools, and the types and power required of machines are usually concerned. Although there are different in energy consumption for all kinds of machine tool, they are very less than those in other generating approaches. According to the energy model proposed by Gutowski et al [10], the overall power required of a machining process depends on the base power demand and the specific power required of the cutting operations. The idle power is the base power demand of equipment features that support the machine tools, such as, power to start-up the computer, motor, coolant pump, and so on. Furthermore, the power consumption in generate a given feature can be deduced by considering its process time, as follows.

\[ P_f = (P_0 + k \cdot MRR) \cdot t \]  \hspace{1cm} (1)

where \( t \) is the required process time for creation of the feature. From equation (1), we can be clearly seen that \( P_0 \) dominates direct power consumption, and depends on the machine tool. Therefore the selection of machine tools has significant impact on the direct power consumption in creation of the feature.

![Fig. 1 Energy profile of total welding operation process: (a) workpiece; (b) load curve](image)
Unlike the cutting features, a welding process not only concerns with the process equipment but several geometry features and actual joining needs. To analyze electrical power consumption of the welding processes, voltage and current are fundamental process parameters, which are supplied by the welding power source.

As shown in Fig.1, there are several events in the energy profile, i.e. the load curve of the welding process, but we can extract a specific the welding process by analyzing it in detail. Then the total energy consumption in the welding process can be estimated from this load curve segment.

Practically, this load curve describes total energy consumption and states of all relative equipment used in actual welding operations. Those include preparation, setup and post processing of machine equipment, etc.

![Load profile of the welding operation](image)

By analyzing the load curve of a welding feature, as shown in Fig.2, the relation between the size of welding seam and the time taken on this welding process is determined. The energy consumption of unit length of the welding seam with given welding approach can be estimated. Also the energy consumption in other stages, such as startup, warming, waiting for operation can be taken into considered. Since the load curve still is not steady as a strict straight line in the actual welding operation stage, averaging is
required in the estimation of energy consumption of the welding seam with unit length. The electrical power consumption of a welding feature can be computed as

\[ P_f = P_s + P_m + P_m' + P_w \]

(2)

Where \( P_s \) represents the electrical power consumption at start up stage, \( P_m \) the consumption of warming up, \( P_m' \) the consumption of waiting, \( P_w \) the consumption during welding operation. After the total consumption is determined in the welding period, assume that \( L \) represents the welding seam length of the welding feature, the electrical power consumption in welding seam with unit length can be computed as

\[ \xi = \frac{P_w}{L} \]

(3)

Once \( P_s, P_m, P_m', \xi \) are obtained for a welding feature they can be stored and used as the parameters of the feature. Then the electrical power consumption for a specific welding feature \( \xi \) with seam length \( L \) can be estimated as

\[ P(\xi) = P_s + P_m + P_m' + \xi \cdot P_w \]

(4)

3. Energy Consumption Model from the Viewpoint of Product

Although the score of a specific feature in the energy and environmental impact can be determined from Section 2, from product viewpoint, all possible schemes with different features should be checked or measured during the design stage and throughout the manufacturing process. To solve this problem, we proposed a general model to capture total energy footprint and ecological footprint. Suppose that \( N \) features of a product need to be generated, and all these possible generating approaches are represented by \( \xi(s, k) \). Where \( s \) is the feature number, which is used for the identification of features \( (s = 1, 2, \ldots, N) \), and \( k \) denotes a specific approach for the generation of features \( (k = 1, 2, \ldots, K) \). The energy efficiency and ecological footprint metrics can be measured as an assignment of a generation approach to a corresponding feature of the part, in such a way, the primary assessment function of energy efficiency and ecological footprint for a part can be defined as follows:

\[ E[p] = \sum_{i=1}^{N} \xi(f(i), m(j)) \]

(5)

Where \( \xi(f, m) \) represents the total energy consumption and ecological footprint of the feature \( f \) by using the specific approach \( m \). In addition, the energy footprint and ecological footprint of the features are defined and used as a two dimensional vector so that the energy and ecological footprint measures could be estimated separately.

4. Experiments

To demonstrate the feasibility of proposed approach, a simple product that consisted of two parts is used. Assume that there are two alternative structures of the product, as shown in Fig.3.
In (a), the disk shape part should be assembled by welding operation. In this case, no shoulder is required in designed for the rotation axis. Against, if cutting features were considered in the assembly of the disk shape part a shoulder would have to be planned, as shown in (b), to locate the disk in the assembly operation. Sometime, a shoulder and rings for shoulder also are required. In this experiment, bar-stocks are used as blanks for the generation of the rotational components. To generate this product with structure (a), the bar-stock is chosen with diameter 100 and length 300. For the structure (b), bar-stock with the diameter 120 and length 300 is used. In this test, the machine tool (MAHO 60) is selected to perform the machining operation, and the welding equipment (HB350) is used to carry out the welding operation. The material removal volume and welding seam length on the components can be determined, further the total energy consumption in generating the two components can be obtained. The results are given in Table 1.

Table 1: Energy required of total manufacturing processes

| products | Material removal Volume ($10^3 mm^3$) | Welding seam Length (mm) | Required Total Energy (J) |
|----------|-------------------------------------|--------------------------|--------------------------|
| Fig.3 (a)| 7.037                               | 282.7433                 | 5895.4                   |
| Fig.3 (b)| 17.719                              | 0                        | 6723.8                   |

5. Conclusion

In this paper, the product design with energy efficiency consideration of manufacturing stage is studied. The concept of manufacturing features is introduced by grouping and definition of various production processes. Moreover, the estimation for the energy consumption of features in the production process is modelled for the evaluation purpose. Although the cutting features and welding features have been only considered and analyzed other features can be modelled by the same way.

However, considering that each of manufacturing feature type has its own characters, it has to be modelled and analyzed in practice. On the other hand, the models for energy consumption are very rough
in current study. Further work should be done to improve the evaluation. It still is a challenge for future research.

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