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Abstract

Purpose – Crane plays a very important role in national economy with greatly reduced labor intensity, improved production efficiency and promoted social development as an indispensable auxiliary tool and process equipment. Therefore, its energy consumption becomes an unavoidable topic and in fact, energy consumption of crane is very huge. It has been proved to be the most cost-effective way for reducing energy consumption to establish and implement new energy efficiency standard. Thus, it is necessary to analyze and evaluate the energy efficiency for overhead crane so as to propose a new energy efficiency standard. The paper aims to discuss these issues.
Design/methodology/approach – In this paper, four kinds of energy consumption sources of overhead crane is considered, based on which, an energy efficiency grading model for overhead crane based on BP neural network is proposed. Second, DS evidential theory is analyzed and based on it, an energy efficiency evaluation model based on BP neural network and DS evidential theory is proposed. The evaluation procedure is discussed in detail. Then, a case is demonstrated how the evaluation is carried out.
Findings – If overhead cranes with different energy consumptions need to be graded according to energy efficiency, the criterions to establish the energy efficiency labels for overhead cranes is proposed in this paper.
Practical implications – The research results can provide energy efficiency standard proposal of overhead crane for relative departments to monitor the design, manufacturing and use of overhead crane.
Originality/value – An energy efficiency grading model for overhead crane based on BP neural network is proposed. An energy efficiency evaluation model based on BP neural network and DS evidential theory is proposed.

Keywords BP neural network, DS evidential theory, Energy efficiency evaluation, Energy efficiency standard, Overhead crane

Paper type Research paper

1. Introduction

Crane is a mechanical device, which is broadly used to transmit materials in modern production. It plays a very important role in the economy of a country and is used as an indispensable auxiliary tool and process equipment for greatly reducing labor intensity, improving production efficiency and promoting social development (Mclntyre *et al.*, 1983). Therefore, its energy consumption becomes an unavoidable topic and in fact, the crane consumes a great deal of energies (Tong *et al.*, 2013). In order to increase energy efficiency of high energy-consumption equipments and people's awareness of energy saving. It has been proved that establishing and implementing new energy efficiency standard is the most cost-effective way for reducing energy consumption. Meanwhile, energy saving can greatly benefit the society (He *et al.*, 2012).

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Currently the energy efficiency in China is labeled in five grades. Wherein grade 1 indicates the energy consumption of product has reached international advanced level with lowest energy consumption, grade 2 indicates low energy consumption, grade 3 indicates the energy consumption reaches the national average level, grade 4 indicates the energy consumption exceeds average, and grade 5 indicates the energy consumed is far more than average ($>$ grade 4) and is not allowed for production and sales (Shen, 2008).

As one of the biggest countries in the world to produce and consume household appliances, the holdings of household appliances revealed a trend of dramatic increase for many years as well as energy consumptions, resulting in severe environment pollution (Wasim *et al.*, 2013). Therefore, Chinese government has established an energy-consumption standard and labels for household appliances to increase the energy efficiency (Jianmin and Jun, 2013), so as to promote the energy saving technology of household appliances and reduce the environment pollution. At present, energy efficiency grading and evaluation for household appliances, like refrigerator and air conditioner, was studied at home and abroad many years ago and is mature now. However, in China for high energy-consuming equipment (such as crane), seldom researches on their energy efficiency grading and evaluation are reported and relative researches still remain at an early stage. As for optimal design of cranes, most researches have been carried from the aspects of structure optimization (Gašić *et al.*, 2011), operation performance optimization (Zhong and Cheng, 2012) as well as energy recovery (Tang *et al.*, 2013). As for energy-consumption evaluation, most researches focus on comparative energy-consumption assessment (not absolute evaluation) based on AHP, fuzzy mathematics and so on (Ye *et al.*, 2013). A energy efficiency comparison test of supply energy, effective energy and energy efficiency was carried out for two typical overhead cranes, and further analysis for the test results were presented with regards to energy efficiency improvement (Cao *et al.*, 2013). For control of overhead cranes, is formulated in an optimal control problem. An optimal control was proposed to search optimal trajectories of velocity and acceleration for minimizing energy consumption from the view of energy consumption and operational safety as well as model predictive control proposed to track optimal trajectories in real-time (Wu and Xia, 2014).

The present work was carried out in order to evaluate the energy efficiency of overhead crane and furthermore propose an energy efficiency standard. In the next section, an energy efficiency grading model for overhead crane based on BP neural network is proposed. In Section 3, an energy efficiency evaluation model based on BP neural network and DS evidential theory is proposed and discussed in detail. In Section 4, a case is studied to demonstrate how the evaluation is made and finally, evaluation results are discussed and research conclusions are summarized.

2. Energy efficiency grading for overhead crane based on BP neural network

2.1 BP neural network

The BP neural network is a learning algorithm which carries out inverse operation for error on a multilayer feed-forward network platform and was proposed by Rumelhart and McClelland in 1985 (Durbin and Rumelhart, 1989). Normally the BP neural network comprises an input layer, a hidden layer and an output layer. The learning process of BP network includes following four parts (Li, 2014):

(1) forward propagation of mode: propagating process from the input layer to the output layer through the hidden layer;

(2) reverse propagation of error: a process in which the link weight is corrected from the hidden layer to the input layer according to the difference between actual output and expected output of BP neural network (Jovanovic *et al.*, 2013);

(3) memory training: a process in which modes (1) and (2) are trained alternatively and repeatedly; and

(4) convergence: a progress the global error of BP neural network comes close to the minimum.

Therefore the learning process of BP neural network can be divided into inverse propagation of error and forward propagation of signal. During its training process, the weight of each layer shall be corrected inversely according to the error calculated from the forward propagation process. After the BP neural network finishes the learning, the weight of each layer can be determined.

2.2 Energy efficiency grading model for overhead crane based on BP neural network

Four kinds of energy-consumption sources of overhead crane (RTS overall energy consumption represented by a1, hoisting mechanism energy consumption represented by a2, traveling mechanism energy consumption represented by a3 and trolley energy consumption represented by a4) are considered in this research, and they are measured as the nodes on the input layer of the neural network. a1, a2, a3 and a4 can be calculated by (output power/input power), which are measured on site. Just like refrigerator and air conditioner, the energy consumption of overhead crane is graded into three levels: grade 1 indicates the overhead crane consumes the lowest energy, grade 2 indicates the energy consumption of overhead crane reaches the average level among similar products, and grade 3 indicates the energy consumption meets the basic operation demands and the overhead crane needs improvements with regard to design and manufacturing when necessary. These three energy efficiency grades for overhead crane correspond to the output layer of BP neural network model and are represented by (1, 0, 0), (0, 1, 0) and (0, 0, 1), respectively. The number of unites of the hidden layer can be determined as follows:

$$m = \sqrt{n+l}+\alpha \tag{1}$$

wherein m denotes the number of hidden layer unites, n denotes the number of input layer unites, l denotes the number of output layer unites and is a random constant between 1 and 10. The energy efficiency grading model for overhead crane based on BP neural network is shown in Figure 1.

3. Hybrid energy efficiency evaluation model for overhead crane

3.1 DS evidential theory

DS evidential theory was proposed by Arthur Dempster and Glenn Shader in the late of 1970s. After 40 years development, DS evidential theory can be used to handle uncertainty caused by either the randomness or the ambiguity and has been broadly used home and abroad. The DS evidential theory is based on the frame of discernment, indicated by θ. The frame of discernment can fully describe all possibilities of a problem and all assumptions resulting from the problem are mutually exclusive. The subset of the frame of discernment is called as proposition. 2^{θ} represents all subsets in the frame of discernment, corresponding to all propositions. The DS evidential theory is used to describe and process uncertainty of information by basic probability assignment function, belief function and likelihood function (Srivastava *et al.*, 2013).

Definition 1. In the frame of discernment θ, A represents an arbitrary subset of the frame of discernment. If in the frame of discernment, there exists a function m:$2^{\theta}\rightarrow[0, 1]$, of which both conditions as follow are satisfied:

(1) $m(\phi)=0$;

(2) $\sum_{A\in\Theta}m(A)=1$

then m can be called as basic probability assignment function of proposition 2^{θ} and m(A) is called as basic probability assignment of A.

Definition 2. In the frame of discernment θ, A represents an arbitrary subset of the frame of discernment. If in the frame of discernment, there exists a function Bel:$2^{\theta}\rightarrow[0, 1]$, of which conditions as follow are satisfied:

(1) $Bel(\phi)=m(\phi)=0$;

(2) $Bel(\theta)=\sum_{B\in\theta}m(B)=1$

(3) $Bel(A_1\cup A_2\cup\cdots\cup A_n)\geqslant\sum_{i}Bel(A_i)-\sum_{i\neq j}Bel\left(A_i\cap A_j\right)+\cdots+(-1)^n\,Bel(A_1\cap A_2\cap\cdots\cap A_n)$

then Bel can be called as belief function.

When $m(\theta)>0$, θ is the focal element of function Bel and also the core of the frame of discernment. Provided functions m and Bel have following relationship:

$$Bel(A)=\sum_{B\in A}m(B) \qquad (2)$$

Definition 3. In the frame of discernment θ, A represents an arbitrary subset of the frame of discernment. If in the frame of discernment,

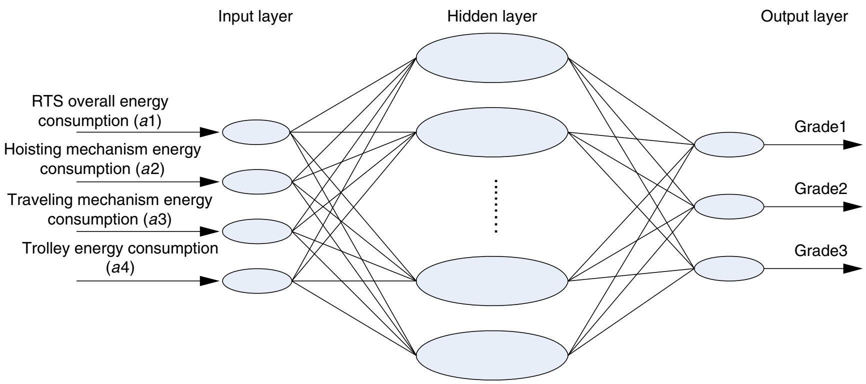

Figure 1. Energy efficiency grading model for overhead crane based on BP neural network

there exists a function $Pls{:}2^{\theta}\rightarrow[0,\ 1]$, of which the condition as follows is satisfied:

$$Pls(A) = 1 - Bel\left(\overline{A}\right)$$

where $\overline{A} = \theta - A$. Then the function Pls is calls as the likelihood function. Provided functions m and Pls have following relationship:

$$Pls(A) = \sum_{B \cap A \neq \varphi} m(B) \tag{3}$$

By comparing Definition 2 with Definition 3, it can be concluded that the evaluation of likelihood function is easier than the evaluation of belief function with less restrictions.

3.2 Dempster's rule of combination

In practical case, evidences could come from various sources. If the practical matter has to be properly evaluated according to the evidences, those evidences shall be fused, which means to fuse different basic probability assignment functions according to the description in Section 3.1.

Provided a frame of discernment θ is provided with two different belief functions Bel_1 and Bel_2 as well as the corresponding basic probability assignment functions $m1$ and $m2$. The focal element of belief function Bel_1 is $A_1, A_2, \ldots, A_K$ and the focal element of belief function Bel_2 is $B_1, B_2, \ldots, B_K$. Also the basic probability assignment functions are $m_1(A_1)$, $m_1(A_2), \ldots, m_1(A_K)$ and $m_2(B_1)$, $m_2(B_2), \ldots, m_2(B_L)$, respectively. Then the combination of both focal elements is illustrated in Figure 2.

Dempster's rule of combination is described in Definition 4:

Definition 4. Provided a frame of discernment θ is provided with basic probability assignment functions which come from n independent evidence sources $m_1, m_2, \ldots, m_n$, Dempster's rule of combination can be defined as follows:

$$\begin{cases} m(\varphi) = 0 \\ m(A) = \frac{\sum_{\cap A_i = A} \prod_{i=1}^{n} m_i(A_i)}{1-k} A \neq \varphi \end{cases} \tag{4}$$

wherein $k = \sum_{\cap A_i = \varphi} \prod_{i=1}^{n} m_i(A_i)$ represents the conflict degree between evidences.

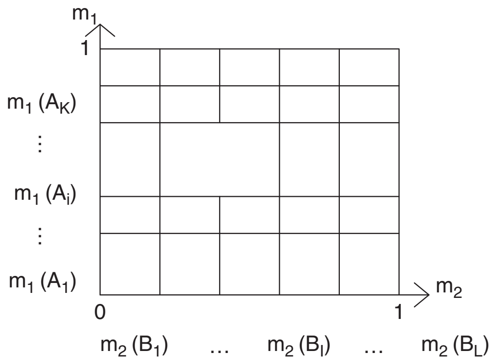

Figure 2.
Combination of focal elements A and B

3.3 Hybrid energy efficiency evaluation model for overhead crane based on BP neural network and DS evidential theory

In order to establish the evaluation model based on BP neutral network and DS evidential theory for energy consumption of overhead crane, first the on-site measuring indexes of overhead crane (a1, a2, a3, a4) are divided into groups (a1, a2, a3), (a1, a2, a3), (a1, a2, a4), (a1, a3, a4) and (a2, a3,a4) represented by NN_1, NN_2, NN_3 and NN_4, respectively. It can be seen that the input of the proposed BP network is designed as $NN_i(a_i, a_j, a_k)^T (i, j, k \in \{1, 2, 3, 4\}, i \neq j, i \neq k, j \neq k)$. The output are designed as $(1, 0, 0)^T$, $(0, 1, 0)^T$ and $(0, 0, 1)^T$, indicating energy efficiency of overhead crane are: grade1, grade2 and grade3 (ordered from high to low efficiency), which are considered as elementary propositions A_1, A_2 and A_3, respectively. If the results output by the BP neural network do not fall into the interval between 0 and 1, a sigmoid function shall be used to normalize the output. Second, let m_i the basic probability assignment function of sub-network NN_i. Then, $m_i(A_i) = a_{il} (l \in \{1, 2, 3\})$, which indicates the basic trust of NN_i of basic proposition A_i and also called as the evidence of event A_i. Finally, according to Dempster's rule of combination described above, the evidences obtained by normalizing the output of BP neural network are fused. The modeling is demonstrated as shown in Figure 3.

4. Case study

Four kinds of energy-consumption sources of overhead crane (RTS overall energy consumption denoted by a1, hoisting mechanism energy consumption denoted by a2, traveling mechanism energy consumption denoted by a3 and trolley energy consumption denoted by a4),which are measured on the site as shown in Table I, are considered in this research for evaluation. Normalization of energy-consumption value is as follows:

$$data_{nn} = (data - \min)/(\max - \min) \tag{5}$$

where $data_m$ refers to normalized data, *data* refers to the measured energy consumption, *max* refers to the maximum energy consumption and *min* refers to the minimum of energy consumption. Then the normalized energy consumptions are listed in Table II. According to the above evaluation model for energy consumption of overhead crane based on BP neural network and DS evidential theory, the data in Table II

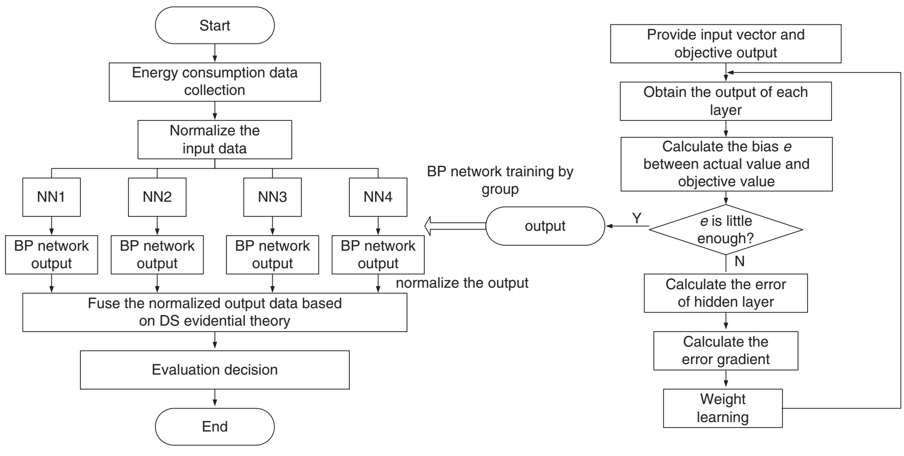

Figure 3. Evaluation procedure of energy efficiency for overhead crane based on BP network and DS evidential theory

Table I.
Measured energy-consumption index

No. (overhead crane)	RTS (%)	Hoisting mechanism (%)	Traveling mechanism (%)	Trolley (%)
1	81	82	81	81
2	82	87	87	84
3	84	81	86	88
4	77	82	77	83
5	75	75	79	87
6	80	77	74	76
7	81	82	87	75
8	73	83	72	71
9	80	81	85	82
10	70	73	72	71

Table II.
Normalized energy consumptions

No. (overhead crane)	RTS (%)	Hoisting mechanism (%)	Traveling mechanism (%)	Trolley (%)
1	0.7860	0.6429	0.6000	0.5882
2	0.8571	1.0000	1.0000	0.7647
3	1.0000	0.5714	0.9333	1.0000
4	0.5000	0.6429	0.3333	0.7059
5	0.3571	0.1429	0.4667	0.9412
6	0.7143	0.2857	0.4706	0.2941
7	0.7860	0.6429	0.1333	0.2353
8	0.2142	0.7143	0.0000	0.0000
9	0.7143	0.5714	0.8667	0.5294
10	0.0000	0.0000	0.0000	0.0000

corresponds to the input data of sub-networks NN_1, NN_2, NN_3 and NN_4 in BP neural network and are used for training samples as listed in Table III. Then MATLAB software is utilized for calculation to train samples after less than 100 times of iterations of each sub-network before. The output results after convergence are listed in Table IV.

By considering the above outputs of BP neural network as evidence based on Dempster's rule of combination as described in Definition 4 the fusion results can obtained, as shown in Table V.

Finally, according to the decision rules (Na and Yu, 2005), which are very important to the hybrid algorithm as described in the following equations, the overhead cranes with different energy consumptions can be graded.

Provided $\exists \mathrm{A}_1, \mathrm{A}_2 \subset \mathrm{U}$, they have following relationship:

$$m(\mathrm{A}_1) = \max\{m(\mathrm{A}_i), \mathrm{A}_i \subset \mathrm{U}\} \tag{6}$$

$$m(\mathrm{A}_2) = \max\{m(\mathrm{A}_i), \mathrm{A}_i \subset \mathrm{U}\&\mathrm{A}_i \neq \mathrm{A}_1\} \tag{7}$$

if:

$$\begin{cases} m(\mathrm{A}_1) - m(\mathrm{A}_2) \succ \varepsilon_1 \\ m(\mathrm{A}_1) \succ \varepsilon_2 \end{cases} \tag{8}$$

then, A_1 can be decided as the corresponding energy-consumption level.

Here, ε_1 and ε_2 are present threshold.

Input of BP neural network-1						
No.		NN1			NN2	
1	0.7860	0.6429	0.6000	0.7860	0.6429	0.5882
2	0.8571	1.0000	1.0000	0.8571	1.0000	0.7647
3	1.0000	0.5714	0.9333	1.0000	0.5714	1.0000
4	0.5000	0.6429	0.3333	0.5000	0.6429	0.7059
5	0.3571	0.1429	0.4667	0.3571	0.1429	0.9412
6	0.7142	0.2857	0.4706	0.7142	0.2857	0.2914
7	0.7860	0.6492	0.1333	0.7860	0.6492	0.2353
8	0.2142	0.7143	0.0000	0.2142	0.7143	0.0000
9	0.7143	0.5714	0.8667	0.7143	0.5714	0.5294
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Input of BP neural network-2						
No.		NN3			NN4	
1	0.7860	0.6000	0.5882	0.6429	0.6000	0.5882
2	0.8571	1.0000	0.7647	1.0000	1.0000	0.7647
3	1.0000	0.9333	1.0000	0.5714	0.9333	1.0000
4	0.5000	0.3333	0.7059	0.6429	0.3333	0.7059
5	0.3571	0.4667	0.9412	0.1429	0.4667	0.9412
6	0.7142	0.4706	0.2941	0.2857	0.4706	0.2941
7	0.7860	0.1333	0.2353	0.6429	0.1333	0.2353
8	0.2142	0.0000	0.0000	0.7143	0.0000	0.0000
9	0.7143	0.8667	0.5294	0.5714	0.8667	0.5294
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table III. Input of BP neural network – 1 & 2

Output of BP neural network-1						
No.		NN1			NN2	
1	1.0000	0.0000	0.0000	0.9999	0.0001	0.0000
2	0.9999	0.0001	0.0000	0.9999	0.0001	0.0000
3	0.9998	0.0002	0.0000	0.9999	0.0001	0.0000
4	0.0000	0.0001	0.9999	0.0000	0.0009	0.9991
5	0.8956	0.1043	0.0001	0.0102	0.9898	0.0000
6	0.0000	0.9999	0.0001	0.0002	0.9872	0.0126
7	0.0003	0.9997	0.0000	0.9999	0.0001	0.0000
8	0.0035	0.9922	0.0043	0.9914	0.0082	0.0004
9	0.0103	0.8865	0.1032	0.0000	0.0029	0.9971
10	0.0004	0.8464	0.1532	0.0000	0.0038	0.9962
Output of BP neural network-2						
No.		NN3			NN4	
1	0.9997	0.0003	0.0000	0.9994	0.0006	0.0000
2	0.9998	0.0002	0.0000	1.0000	0.0000	0.0000
3	0.9999	0.0001	0.0000	0.9989	0.0011	0.0000
4	0.0000	0.0003	0.9997	0.0000	0.9995	0.0005
5	0.1135	0.8745	0.0120	0.8982	0.1006	0.0012
6	0.0003	0.9976	0.0021	0.0001	0.9997	0.0002
7	0.9996	0.0004	0.0000	0.9998	0.0002	0.0000
8	0.0014	0.9986	0.0000	0.9988	0.0012	0.0000
9	0.0046	0.9943	0.0011	0.0012	0.9832	0.0156
10	0.0000	0.9977	0.0023	0.0008	0.0001	0.9991

Table IV. Output of BP neural network – 1 & 2

Table V.
Evaluation fusion based on Dempster's rule of combination

No.	a1 (%)	a2 (%)	a3 (%)	a4 (%)	Fusion results based on Dempster's rule of combination		
1	81	82	81	81	1.0000	0.0000	0.0000
2	82	87	87	84	1.0000	0.0000	0.0000
3	84	81	86	88	1.0000	0.0000	0.0000
4	77	82	77	83	0.0000	0.9748	0.0252
5	75	75	79	87	0.0930	0.9070	0.0000
6	80	77	74	76	0.0000	1.0000	0.0000
7	81	81	87	75	0.0000	0.9993	0.0007
8	72	83	72	71	0.3323	0.6677	0.0000
9	80	81	85	82	1.0000	0.0000	0.0000
10	70	73	72	71	0.0000	0.0009	0.9991

From Table V, according to the experts from enterprises and national management ministry, ε_1 and ε_2 are set as 0.3 and 0.65, respectively. Therefore, it is decided to grade the ten overhead cranes by energy efficiency into three levels: grade1 (no. 1-no. 3 and no. 7), grade2 (no. 4-no. 6, no. 8 and no. 9) and grade3 (no. 10).

5. Results discussion and conclusions

If overhead cranes with different energy consumptions need to be graded according to energy efficiency, it is proposed in this paper to use the following criteria to establish the energy efficiency labels for overhead cranes.

Grade1 – energy efficiency of RTS $\eta \geqslant 80$ percent; energy efficiency of lifting mechanism $\eta_1 \geqslant 80$ percent; energy efficiency of traveling mechanism $\eta_2 \geqslant 80$ percent; and energy efficiency of trolley $\eta_3 \geqslant 80$ percent. If the energy efficiencies of overhead crane can satisfy the criteria of grade 1, it can be considered to have reached the international advanced level.

Grade 3 – energy efficiency of RTS $\eta \leqslant 75$ percent; energy efficiency of lifting mechanism $\eta_1 \leqslant 75$ percent; energy efficiency of traveling mechanism $\eta_2 \leqslant 75$ percent; and energy efficiency of trolley $\eta_3 \leqslant 75$ percent. If the energy efficiencies of overhead crane fall into the level of grade 3, it is considered below the average level in China. Therefore the crane shall be improved or even prohibited.

Grade2 – energy efficiency between grade 1 and grade 3, as average in China.

The present work seeks to evaluate the energy efficiency of overhead crane and furthermore propose an energy efficiency standard for related departments to monitor the design, manufacturing and use of overhead crane. The evaluation results can help to find where the high consumption lies in and to improve energy efficiency. The proposed energy efficiency standard, on one hand, can help to promote the high energy-consumption products upgrading into green products, and on the other hand, can favor the use and maintenance of overhead crane.

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