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ORIGINAL ARTICLE

Research on eco-balance with LCA and LCC for mechanical product design

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Abstract Life cycle assessment (LCA), as an assessment tool for environmental performance, is used widely in decision making of product design. However, apparently, it is not sufficient to make final decision only depending on environmental assessment results for profit-directed organizations. One of the main purposes of this paper is to propose a methodology for integration of LCA and economic analysis tool-life cycle costing (LCC) in order to get the integrated evaluation results. A framework of integration of LCA and LCC has been introduced, which is contained by four components: the definition of unity time and physical boundaries, integration of inventory analysis, integration of impact assessment, environmental and economic interpretation. However, the integrated evaluation results always indicate that the relationship between economic and environmental performance is not in balance. Optimization is as important as integration to eco-balance. An optimization method is proposed to improve the initial product design with maximizing the integrated environmental and economic benefit for mechanical product. In optimization step, product system is divided two parts with environmental subsystem and economic subsystem. The integrated evaluation results are adopted to support for the optimization. Some mathematic optimization models are set up for environmental and economic subsystems. Multidisciplinary design optimization is applied to optimize these models so that the initial mechanical product design can achieve the best environmental and economic performance result. A case study of type 4135G diesel engine is presented to validate the rationality and feasibility.

Keywords Eco-balance · Integration · Life cycle assessment (LCA) · Life cycle costing (LCC) · Multidisciplinary design optimization (MDO)

1 Introduction

As environmental protection is becoming more and more important, green manufacturing has become an expected practice that should be integrated in the development of industry [1]. Life cycle assessment (LCA) is used widely in decision making of product design as an assessment tool for environmental performance [2]. However, LCA typically does not address the economic or social aspects of a product. It limits the influence and relevance of LCA in decision making [3]. Product designers cannot make final decision only depending on environmental assessment results. So it is necessary to integrate LCA and other economic analysis tool.

Many attempts have been made at integrating the assessment of environmental and economic performance of alternative products or product design decision. The economic analysis tool mostly used in integrating with LCA is called life cycle costing (LCC). Currently there are two main methods applied in integrating LCA and LCC. One method is to integrate economic considerations into the process of LCA. Norris [4] points out that standard methods of LCA can and have been integrated with standard methods for cost accounting, life cycle cost analysis, and scenario-based economic risk modeling. Reich [5] brings forward the terminology for economic assessment and develops the method

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of combining the financial LCC, environmental LCC and LCA. Bovea et al. [6] establish a model which is based on the combination of three LCC methods: (1) to evaluate the environmental requirements comprised of LCA, (2) to examine the internal and external costs of the product, and (3) to contingent valuation. Campbell et al. [7] proposed a technology and economic evaluation method to reduce shielding gas consumption. The other method calculates environmental cost by integrating LCA and LCC. Steen [8] uses LCA results to identify and estimate environmental costs or benefits in an LCC. Senthil et al. [9] develop a life cycle environmental cost analysis model by incorporating costing into the LCA practice. Góralczyk et al. [10] provide a new tool to evaluate the economic and ecological feasibility of a project using a combination of environmental goals. Georgiadis et al. [11] use dynamics idea to analysis environmental and economical sustainability for WEEE closed-loop supply chains with recycling. However, a consistent method has not been proposed in overcoming the inconsistencies in timing of emissions and economic activities, and system boundaries. Moreover, further research on how to improve and optimize the initial design after getting the integrated evaluation result has not been mentioned. Karen [12] gives an optimization method for the floor design in residential buildings.

In the process of product design, the integrated evaluation result often indicates that the relationship between economic and environmental performance is not in balance [13–15]. It means that optimization is as important as integration. This paper tries to use multidisciplinary design optimization (MDO) to acquire the optimal value of the critical factors [16]. MDO can help to take advantage of that synergy and to maximize the integrated environmental and economic benefit.

In this study, an integrated assessment method is proposed to comprise of definition of boundary (time boundary and physical boundary), integration of inventory data, and integration of impact assessment between LCA and LCC. Meanwhile by getting environmental evaluation results, the integrated benefit evaluation, important relationships, and trade-offs between the economic and environmental performance are also characterized. Based on the integrated evaluation, a mathematic model based on MDO is proposed to achieve best environmental and economic performance for the initial product design.

2 The framework of integration

LCC can be divided into two parts, environment-related LCC (ER-LCC) and non-environment-related LCC (NER-LCC). ER-LCC is generated by environmental factors related to LCA, such as raw material cost, fuel cost, cost for disposal of environmental emission, etc. NER-LCC has nothing with environmental factors, such as management cost, design cost, etc. This paper aims to get the integrated evaluation results by establishing the relationship between environmental and economic performance. Therefore, the NER-LCC is not necessary to be calculated. The cost mentioned in following is ER-LCC.

As shown in Fig. 1, the unity time and physical boundaries are defined for ER-LCC and LCA. The physical boundary includes each process that has both environmental and economic attribute. Environmental or economic inputs get into each corresponding process across the defined boundary. The environmental and economic outputs constitute the initial data of inventory analysis. The processes such as design, marketing, and storage, etc., which refer to the NER-LCC, are not considered. The integrated inventory data is evaluated by

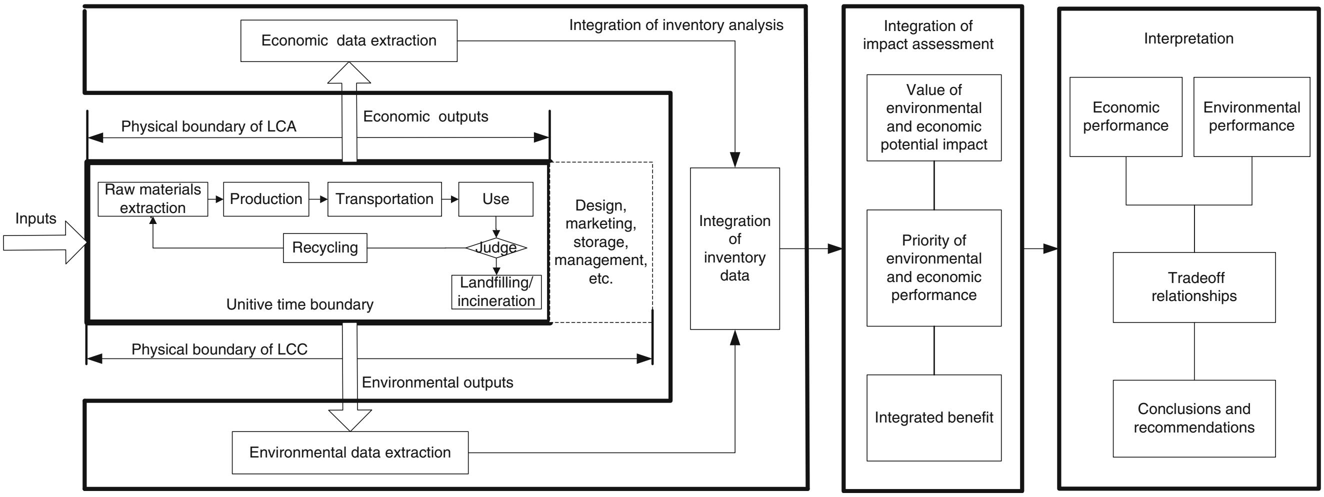


Fig. 1 The integrated framework of ER-LCC and LCA

impact assessment. The interpretations on both economic and environmental performance and their trade-offs are given to derive recommendations and conclusions.

3 Integration method of ER-LCC and LCA

3.1 Definition of boundary

It is necessary to define the unity time boundary to match the economic calculations to the LCA calculations. The comparison of life-cycle time axes of LCA and LCC is illustrated in Fig. 2. The time boundary is defined as the period from raw material extraction to final disposal, i.e., from point A to point B. ER-LCC is discounted back to point C as the initial period of time boundary.

Physical boundary is to define the objects of analysis in the process of integrated assessment. The objects of analysis are the processes throughout the life cycle. In order to make LCA and ER-LCC have the unitive system boundary throughout integration, each chosen process such as production, transportation, use, and final disposal, etc., must have both environmental and economic attributes.

3.2 Matrix-based integration of inventory data

The integrated inventory data leads to LCA dynamic calculation and data analysis along with time. Meanwhile, the cost function is distributed into each process analysis [17]. The steps of algorithm for integration of inventory data are illustrated as follows:

- Propose hypotheses and compartmentalize unit process. ER-LCC is calculated by each unit process cost including the cost generated by “inputs” and cost for disposal of environmental outputs. If the inputs of current process are derived from the outputs of former process, the calculation of cost should be ignored in order to avoid the repeated calculation. The cost occurring in different time periods should be discounted back to point C. Unit processes are compartmentalized in the physical boundary and the original environmental I/O of each unit process are known.
- Construct an “input-process” matrix $A=(a_{ij})_{m\times n}$, where a_{ij} indicates the quantity of environmental input factor i in the process j, $a_{ij}\geq 0$; m is the number of categories of input factor ; n is the number of defined unit processes.
- Construct an “environmental output-process” matrix $E=(e_{ij})_{3\times n}$, where e_{ij} indicates in the process j the quantity of environmental output factor i which will not get into the next process, $e_{ij}\geq 0$; 3 indicates the three environmental output factors including exhaust gas, solid waste, liquid waste; n is the number of defined unit processes.
- Construct a summation matrix $B=(1,1,\ldots,1)^T_{b\times 1}$, where b is determined by the number of column of matrix which multiplies with B.
- Construct a matrix $C=(c_{11}, c_{21},\ldots, c_{m1})^T_{m\times 1}$ and a matrix $D=(d_{11}, d_{21}, d_{31})^T$, where c_{i1} indicates the unit price of environmental input factor i in the matrix A; d_{i1} indicates the unit price of disposal of environmental output factor i in the matrix E.
- Cite the cost function: $PV=F\times(1+q)^{-y}$, where PV indicates the present value of future cost F over time y discounted with interest rate q (unit of y: year).
- Establish the relationship of matrix A, matrix E, and ER-LCC. In any row of matrix A or matrix E, each element denotes the quantity of the same environmental input or output in different processes. Although the elements in the same row have the same price, there are intervals between different elements. It is not proper to discount all the cost of environmental inputs and outputs in matrix A and matrix E after summing up. Therefore, the matrix K_1 and matrix K_2 are constructed in order to establish the direct relationship of matrix A, matrix E, and ER-LCC.

$$K_1=\begin{bmatrix} k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \\ k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \\ \cdots & \cdots & k^{t_1+t_2+\cdots+t_j} & \cdots \\ k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \end{bmatrix}_{m\times n}$$

$$K_2=\begin{bmatrix} k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \\ k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \\ k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \end{bmatrix}_{3\times n}$$

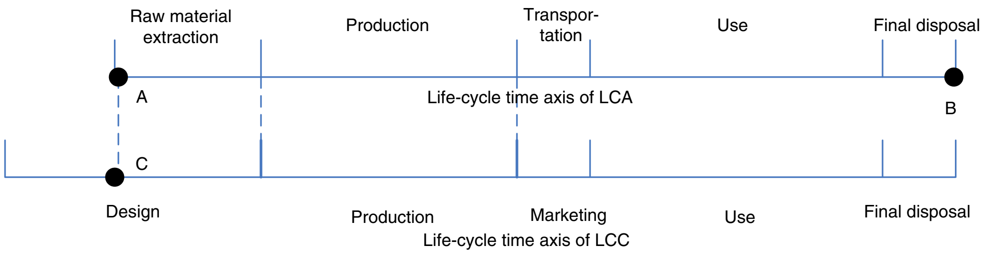


Fig. 2 The life-cycle time axes of LCA and LCC

Where $k = 1/(1+q)$; t_j is the time of process j. Let "o" indicates Hadamard Product. Then,

$$A \circ K_1 = \left(a_{ij} \times k^{t_1+t_2+\cdots+t_j}\right)_{m\times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & a_{ij} & \cdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \circ \begin{bmatrix} k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2\cdots+t_j+\cdots+t_n} \\ k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2\cdots+t_j+\cdots+t_n} \\ \cdots & \cdots & k^{t_1+t_2} & \cdots \\ k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2\cdots+t_j+\cdots+t_n} \end{bmatrix}$$

$$E \circ K_2 = \left(e_{ij} \times k^{t_1+t_2+\cdots+t_j}\right)_{3\times n} = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ e_{31} & e_{32} & \cdots & e_{3n} \end{bmatrix} \circ \begin{bmatrix} k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \\ k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \\ k^{t_1} & k^{t_1+t_2} & \cdots & k^{t_1+t_2+\cdots+t_j+\cdots+t_n} \end{bmatrix}$$

According to the requirement of Hadamard Product, matrix C must be changed into matrix C^* which has the same order $m \times n$ with matrix A, and matrix D is also changed into $3 \times n$ matrix D^*. The matrix C^* and D^* are as follows:

$$C^* = \begin{bmatrix} c_{11} & c_{11} & \cdots & c_{11} \\ c_{21} & c_{21} & \cdots & c_{21} \\ \cdots & \cdots & \cdots & \cdots \\ c_{m1} & c_{m1} & \cdots & c_{m1} \end{bmatrix}_{m\times n} \qquad D^* = \begin{bmatrix} d_{11} & d_{11} & \cdots & d_{11} \\ d_{21} & d_{21} & \cdots & d_{21} \\ d_{31} & d_{31} & \cdots & d_{31} \end{bmatrix}_{3\times n}$$

Then, ER-LCC matrix EC is defined as Eq.(1):

$$EC = \left[(A \circ K_1) \circ C^*\right]^T \times B_{m\times 1} + \left[(E \circ K_2) \circ D^*\right]^T \times B_{3\times 1} \tag{1}$$

The matrix EC is of order $n \times 1$. Each element of matrix EC indicates the ER-LCC of each process. $\sum EC_i$ denotes the discounted ER-LCC of all the objects in physical boundary.

It takes time into account in the integration of environmental and economic factors. Cost function is distributed into each process in life cycle by matrix K_1 and matrix K_2. Consequently, the relationship between environmental and economic performance is established, and the integrated inventory data is carried out.

3.3 The integration of impact assessment

The integrated impact assessment is a quantitative and/or qualitative process to identify, characterize, and assess the potential environmental and economic impacts. Based on the SETAC methodology (classification, characterization, normalization, and valuation), an improved method which takes economic assessment into account is proposed. It consists of five steps of classification, characterization, normalization, weighting determination, and integrated benefit assessment. The weights for environmental and economic indices are identified by analytic hierarchy process (AHP). The four-layer impact assessment index system is shown in Fig. 3.

However, environmental and economic indices have different dimension. In order to convert indicator results of different impact categories to a common scale, a converting design index method is used to get the dimensionless environmental index $I_{\text{environmental}}$ and the dimensionless economic index I_{economic}.

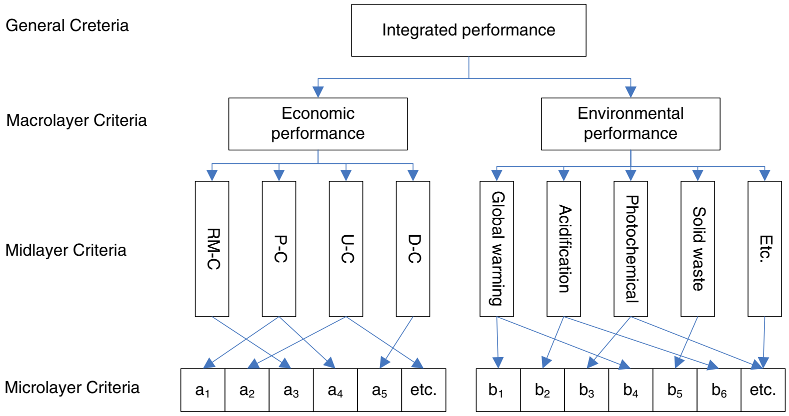
Integrated benefit index $I_{\text{integration}} = \lambda_1 \times I_{\text{environmental}} + \lambda_2 \times I_{\text{economic}}$, where λ_1 and λ_2 indicate the weights for environmental and economic indices. The integrated benefit index can be as a comparable parameter in decision making of product design. If the integrated benefit index is lower, it is better.

4 Optimization based on MDO algorithm

4.1 The critical factors for optimization

There are many factors to impact the environmental and economic benefit. The critical factors that can be controlled

Fig. 3 The four-layer impact assessment index system



Note: RM-C: raw material extraction process cost; P-C: production process cost;
U-C: use process cost; D-C: disposal process cost
a_i:Sub-categories of cost elements, such as material cost, environmental disposal cost, etc;
b_i:Environmental outputs, such as carbon dioxide, etc.

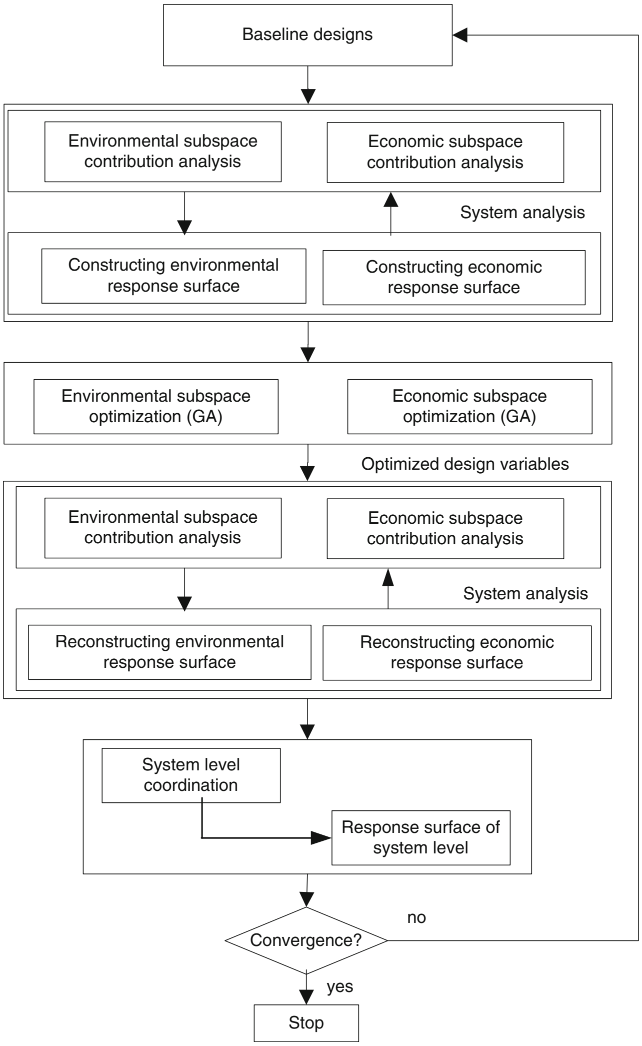


Fig. 4 The flow of optimization algorithm based on CSS0/NN

in product design are raw material type and product structural parameters. They are intimately related to the final environmental and economic performance. A product consists of several parts with different structural parameters according to design requirements. Each part has various choices in terms of different types of raw material. Therefore, the goal of optimization is to determine the optimal structural parameters and the combined scheme of raw material for the product. So the integrated benefit should be maximized.

The product structural parameters, raw materials, environmental impact, and cost are coupling. They may be continuous design variables or discrete design variables. The CSSO/NN algorithm is one of appropriate methodologies to solve multidisciplinary optimization with mixed variables. It may optimize collaterally and effectively with subspaces (shown as Fig. 4).

1. The structure parameters of initial product design .The structure parameters which have significant impact on the environmental and economic performance are length parameters and diameter parameters.
    - Length parameters:$L=\{l_1,l_2,l_3,\ldots,l_i,\ldots,l_n\}$, where n indicates the number of parts which constitute the product ; l_i is the length of part i, $l_i>0$.
    - Diameter parameters:$D=\{d_1,d_2,d_3,\ldots,d_i,\ldots,d_n\}$, where n indicates the number of parts; d_i is the diameter of part i, $d_i\geq0$ (when the part i do not have the diameter parameter, $d_i=0$).
2. The raw material type and the weight of parts in initial design (Table 1). The raw material type is represented with density. P_{im} and c_{im} denote the density and price of the m optional raw material type of part i, where $m=1, 2, \ldots, k_i$. k_i is the number of optional raw material types of part i.
3. The integrated evaluation results of initial design (Table 1). They are the synthetic values of potential impact to environment, the ER-LCC of each life process and the weights of economic indices.
4. The weights of environmental and economic performance of initial product design. They are λ_1 and λ_2.

4.2 The optimization model

1. To determine the design variables. To make sure the universality of CSSO/NN algorithm in the optimization system, it defines three kinds of part showed in Table 2. They include the length parameters only, or the diameter parameters only, or the diameter parameters and the length parameters.

   X_i is continuous variable, and P_i, c_i are discrete variables, $P_i\in P_{im}, c_i\in c_{im}$.
2. To build the models for environmental and economic subspaces.

Table 1 The data in initial design

Parts	Raw material type	Price	Weight of part	Density and price	Synthetical value of potential environmental impact	ER-LCC of raw material extraction, production, use, and final disposal	Weights of ER-LCC of raw material extraction , production, use, and final disposal
Part i	P_i^0	c_i^0	A_i	P_{im},c_{im}	Y_i^0	$C_{i1}{}^0, C_{i2}{}^0, C_{i3}{}^0, C_{i4}{}^0$	$W_{i1}, W_{i2}, W_{i3}, W_{i4}$

Table 2 The three kinds of part

Part	Diameter	Length	Raw material type	Price
Part I	–	X_1	P_1	c_1
Part II	X_2	–	P_2	c_2
Part III	X_3	X_4	P_3	c_3

The environmental subspace is carried out by Eqs. (2–4):

$$\text{Part I} : Y_1 = Y_1^0 \times \frac{X_1 P_1}{l_1 P_1^0} \tag{2}$$

$$\text{Part II} : Y_2 = Y_2^0 \times \frac{X_2^2 P_2}{d_2^2 P_2^0} \tag{3}$$

$$\text{Part III} : Y_3 = Y_3^0 \times \frac{X_3^2 X_4 P_3}{d_3^2 l_3 P_3^0} \tag{4}$$

The economic subspace is carried out by Eqs. (5–7):

$$\text{Part I} : C_1 = \frac{Y_1}{Y_1^0}\left(W_{11}C_{11}^0\frac{c_1}{c_1^0} + W_{12}C_{12}^0 + W_{13}C_{13}^0 + W_{14}C_{14}^0\right) \tag{5}$$

$$\text{Part II} : C_2 = \frac{Y_2}{Y_2^0}\left(W_{21}C_{21}^0\frac{c_2}{c_2^0} + W_{22}C_{22}^0 + W_{23}C_{23}^0 + W_{24}C_{24}^0\right) \tag{6}$$

$$\text{Part III} : C_3 = \frac{Y_3}{Y_3^0}\left(W_{31}C_{31}^0\frac{c_3}{c_3^0} + W_{32}C_{32}^0 + W_{33}C_{33}^0 + W_{34}C_{34}^0\right) \tag{7}$$

3. To built the objective function.

The weights of the three kinds of parts are:

$$Q_i = A_i \Big/ \sum_{i=1}^{3} A_i \tag{8}$$

The objective function of environmental subspace is defined as Eq.(9):

$$\min Y = Q_1 \times Y_1 + Q_2 \times Y_2 + Q_3 \times Y_3 \tag{9}$$

The objective function of economic subspace is defined as Eq.(10):

$$\text{Minimize} : C = Q_1 \times C_1 + Q_2 \times C_2 + Q_3 \times C_3 \tag{10}$$

The objective function of system level is the combination of environmental and economic indices. Because they have different dimension, a converting design index method is used to make these indices dimensionless.

$$\begin{aligned}
(a)\ & Q_1 Y_1^0 + Q_2 Y_2^0 + Q_3 Y_3^0 = \text{Constant} = \beta_1 \\
& X_{j1} = \tfrac{1}{\beta_1}(Q_1 \times Y_1 + Q_2 \times Y_2 + Q_3 \times Y_3) \times 2\pi \\
& F_1(X) = \tfrac{X_{j1}}{2\pi} - \sin X_{j1} \\
(b)\ & Q_1 \times \left(C_{11}^0 + C_{12}^0 + C_{13}^0\right) + Q_2 \times \left(C_{21}^0 + C_{22}^0 + C_{23}^0\right) + \\
& Q_3 \times \left(C_{31}^0 + C_{32}^0 + C_{33}^0\right) = \text{Constant} = \beta_2 \\
& X_{j2} = \tfrac{1}{\beta_2}(Q_1 \times C_1 + Q_2 \times C_2 + Q_2 \times C_2) \times 2\pi \\
& F_2(X) = \tfrac{X_{j2}}{2\pi} - \sin X_{j2}
\end{aligned}$$

The objective function of system level is defined as Eq.(11):

$$\text{Minimize} : F(X) = \lambda_1 F_1(X) + \lambda_2 F_2(X) \tag{11}$$

4. To built response surface optimization model based on CSSO/NN

According to the precise system model, the corresponding state variables may be found out by the design variables, and the parallel subspace optimization model can be built. Firstly, the approximate relationship function between design variables and state variables is built. In environmental subsystem, the design variables X_1, X_2, X_3, X_4 and raw material choice variables P_1, P_2, P_3 are mapped as state variables. So, the environmental potential impact value of the three kinds of parts are $Y_1{}^0$, $Y_2{}^0$, $Y_3{}^0$. Secondly, the discrete variables c_1, c_2, c_3 in cost subsystem and the state variable $Y_1{}^0$, $Y_2{}^0$, $Y_3{}^0$ in environmental subsystem are

Table 3 Matrix A for input-process

Inputs	Phases	Raw material extraction	Production	Use	Final disposal
Water (kg)		15,357.80	0.00	4,000.00	0.00
Limestone (kg)		767.89	0.00	0.00	0.00
Pig iron (kg)		406.51	0.00	0.00	0.00
Oxygen (kg)		370.16	0.00	1,738.00	0.00
Base oil (kg)		67.76	0.00	0.00	0.00
Ore(kg)		74.68	0.00	0.00	0.00
Electricity (kwh)		1,916.94	122.31	0.00	0.00
Fuel (kg)		33.09	0.00	0.00	3.44
Coal (kg)		513.77	0.00	0.00	0.00
Grinding fluid (kg)		0.00	18.16	0.00	0.00
Diesel oil (kg)		0.00	0.00	7,200.00	0.00

Note: Ore in inputs includes clunch, olivine, manganese ore, bentonite, dolomite, fluor, grit, alumyte, etc. All of them are the inputs only in raw material extraction. So they can be grouped into single type, i.e., ore

Table 4 The integrated inventory data of 4135G model diesel engine

Phases	ER-LCC of phases (unit: Yuan)	Inputs			Outputs		
		Name	Unit	Value	Name	Unit	Value
Raw material extraction	2,776.73	Water	kg	15,357.80	Steel	kg	366.90
		Limestone	kg	767.89	Slag	kg	1,797.77
		Pig iron	kg	406.51	Solid waste	kg	397.68
		Oxygen	kg	370.16	Dusts	kg	155.17
		Base oil	kg	67.76	Suspended matter	kg	54.45
		Clunch	kg	28.46	NH_4^+	kg	0.45
		Olivine	kg	17.62	COD	kg	0.13
		Manganese ore	kg	10.84	BOD	kg	0.002
		Dolomite	kg	6.32	Hydroxy benzene	kg	0.002
		Fluor	kg	5.87	Na^+	kg	0.17
		Grit	kg	2.53	CO	kg	49.69
		Bentonite	kg	2.17	CO_2	kg	3,703.94
		Alumyte	kg	0.68	SO_x	kg	23.04
		Azotes	kg	0.005	NO_x	kg	7.23
		Sulfur	kg	0.001	H_2S	kg	0.04
		Electricity	kw.h	1,916.94	HCl	kg	0.04
		Fuel	kg	33.09	Hydrocarbon	kg	0.86
		Coal	kg	513.77	Firedamp	kg	8.13
Production	89.76	Rough	kg	366.90	Product	kg	317.10
		Grinding fluid	kg	18.16	Swarf	kg	49.8
		Electricity	kw.h	122.31			
Use	14,437.09	Diesel oil	kg	7,200.00	CO	kg	474.00
		Oxygen	kg	1,738.00	CO_2	kg	2,212.00
		Azotes	kg	2.91	HC	kg	169.5
		Water	kg	4,000.00	NO_x	kg	15.80
					Heat energy	MJ	237,600
Final disposal	4.98	Fuel	kg	3.44	Recycled iron	kg	221.97
					Waste iron (landfill)	kg	95.13

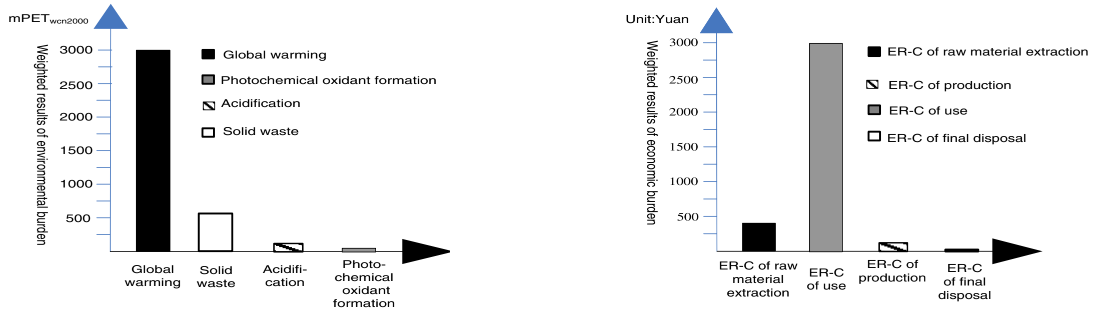
mapped as state variables. So, the economy potential impact value of the three kinds of parts are C_1^0, C_2^0, C_3^0. Finally, in the system layer, the objective function value *F(X)* is carried out through all the known design variables and state variables under the limited constraint conditions. All the state variables are directly obtained from the response surface in each subsystem. Therefore, the response surface approximation is at a very fast rate

5. Subsystem optimization based on genetic algorithm

Heuristic algorithm can search direction and keep good solution by some mechanisms, but not rely on the sensitivity

Table 5 Normalized environmental, economic burden, and weights of impact categories

Impact categories		ER-LCC of raw material extraction	ER-LCC of production	ER-LCC of use	ER-LCC of final disposal
Economic burden	Normalized results	2,776.73	89.76	14,437.09	4.98
	Weights (λ_i)	λ_1=0.14	λ_2=0.03	λ_3=0.21	λ_4=0.01
Impact categories		Global warming	Solid waste	Acidification	Photochemical oxidant formation
Environmental burden	Normalized results	9,875.82	2,529.71	39.60	23.00
	Weights (λ_i)	λ_5=0.32	λ_6=0.21	λ_7=0.06	λ_8=0.02



(a) Weighted results of environmental burden (b) Weighted results of economic burden

Fig. 5 Weighted results of environmental and economic burden

information, according to the physical mapped “fitness” information. It has a big probability to find global optimal solution. Therefore, the genetic algorithm (GA) is used as an optimization tool in subspace optimization and system level optimization. The GA parameter debugging is conducted through operation tests in the subspace and system layer. In optimization process, the state variables information in other disciplines can be obtained through the response surface.

5 Case study

A case of type 4135G diesel engine is presented. There are two steps: firstly to evaluate the integrated performance of such diesel engine, and secondly to optimize the product design to maximize the integrated benefit.

The functional unit is a type 4135G diesel engine. A diesel engine consists of large numbers of parts which include huge amounts of unit processes and corresponding data in the life cycle. The diesel engine is simplified as follows:

1. To select the objects. Four kinds of parts which carry out the main function of diesel engine are selected.
   - Cylinder block 228.00 kg one piece;
   - Connecting rod 6.03 kg four pieces;
   - Piston 3.08 kg four pieces;
   - Crankshaft 52.55 kg one piece.
2. To suppose that the raw material types of parts in initial design are common steel.
3. To divide the input/output of each production process into four types, i.e., semi-manufactured goods, electric energy, swarf, and grinding fluid.
4. To suppose the final disposal includes 70 % recycle and 30 % landfill.

The raw material and diesel engine are generally manufactured using an original equipment manufacturing. The case is performed under the following assumptions and limitations. When the life cycle environmental inventory data is not available, we will use data from the China national environmental databases. All the economic data is obtained from the China national database [18–20].

5.1 The definition of boundary for the researched diesel engine

The time boundary is defined from raw material extraction, through production and application to final disposal. Suppose the year of 2010 as the original point of raw material extraction. ER-LCC of each lifecycle process is discounted back to original point. Physical boundary contains every unit process of raw material extraction, production, use, and final disposal.

5.2 Integrated inventory analyses

The process time is the summation of process executing time, waiting time, and transportation time before or after the process. Generally, the raw material and mechanical products are produced or transported in batches. Therefore, the process time is estimated in batches according to the average productivity of domestic steel industry and mechanical industry:

- The process time of production of raw material (common steel): t_1=0.12 year;

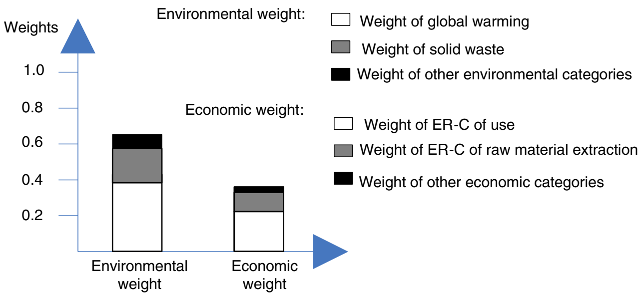


Fig. 6 Comparison of environmental and economic weights

Table 6 The structure parameters of diesel engine in initial design

Structure parameters Part	Piston Part I	Cylinder block Part II	Connecting rod Part III	Crankshaft (main journal) Part IV
Length	l_1=140.00 mm	——	l_3=110.00 mm	l_4=50.00 mm
Diameter	——	d_2=135.00 mm	d_3=90.00 mm	d_4=110.00 mm

- The process time of production of diesel engine: t_2=0.04 year;
- The process time of use: t_3=5 year (suppose the life expectancy of diesel engine is 150,000 km, and the average running mileage per year is 30,000 km);
- The process time of final disposal: t_4=0.08 year.
- In case of the average discount rate *(q)* during the year of 2004–2010 is 15 %, then $k=1/(1+q)$=0.87.
- Construct "input-process" matrix A, whose vectors are listed in Table 3.
- Construct "environmental output-process" matrix *E*. The row vectors denote the exhaust gas, solid waste, liquid waste. The column vectors denote the four life cycle phases of raw material extraction, production, use, final disposal.

$$E=\begin{bmatrix} 2392.93 & 0.00 & 2871.31 & 0.00 \\ 2405.07 & 49.82 & 0.00 & 95.13 \\ 1.15 & 0.00 & 0.00 & 0.00 \end{bmatrix}$$

1. Construct matrix C^* and matrix D^*. The elements indicate the unit price of relevant inputs of matrix *A* and outputs of matrix *E*. The unit is Yuan per kilowatt hour or Yuan per kilogram.

$$C^*=\begin{bmatrix} 0.002 & 0.12 & 1.05 & 0.00 & 3.23 & 0.87 & 0.70 & 1.50 & 0.56 & 0.12 & 3.05 \\ 0.002 & 0.12 & 1.05 & 0.00 & 3.23 & 0.87 & 0.70 & 1.50 & 0.56 & 0.12 & 3.05 \\ 0.002 & 0.12 & 1.05 & 0.00 & 3.23 & 0.87 & 0.70 & 1.50 & 0.56 & 0.12 & 3.05 \\ 0.002 & 0.12 & 1.05 & 0.00 & 3.23 & 0.87 & 0.70 & 1.50 & 0.56 & 0.12 & 3.05 \end{bmatrix}^T \quad D^*=\begin{bmatrix} 0.05 & 0.05 & 0.05 & 0.05 \\ 0.08 & 0.08 & 0.08 & 0.08 \\ 0.03 & 0.03 & 0.03 & 0.03 \end{bmatrix}$$

The matrix K_1, matrix K_2, and matrix *B* are as follows:

$$K_1=\begin{bmatrix} 0.983 & 0.983 & 0.983 & 0.983 & 0.983 & 0.983 & 0.983 & 0.983 & 0.983 & 0.983 & 0.983 \\ 0.978 & 0.978 & 0.978 & 0.978 & 0.978 & 0.978 & 0.978 & 0.978 & 0.978 & 0.978 & 0.978 \\ 0.487 & 0.487 & 0.487 & 0.487 & 0.487 & 0.487 & 0.487 & 0.487 & 0.487 & 0.487 & 0.487 \\ 0.482 & 0.482 & 0.482 & 0.482 & 0.482 & 0.482 & 0.482 & 0.482 & 0.482 & 0.482 & 0.482 \end{bmatrix}^T \quad K_2=\begin{bmatrix} 0.983 & 0.978 & 0.487 & 0.482 \\ 0.983 & 0.978 & 0.487 & 0.482 \\ 0.983 & 0.978 & 0.487 & 0.482 \end{bmatrix}$$

Table 7 The weight and optional raw material types of each part in initial design

Parts	Optional raw material types	Density(P_{im})	Price (c_{im})	Weight (A_i)
Part I	Al–Cu–Ni–Mg multi-components Al–Si–Ni–Mg–Cu multi-components	P_{11}=3.50 g/cm^3 P_{12}=4.20 g/cm^3	c_{11}=3,747.00Yuan/t c_{12}=4,082.00Yuan/t	A_1=3.08 kg (four pieces)
Part II	Cast iron Aluminum alloy	P_{21}=7.80 g/cm^3 P_{22}=2.70 g/cm^3	c_{21}=4,000.00Yuan/t c_{22}=4,350.00Yuan/t	A_2=228.00 kg (one piece)
Part III	45 medium carbon steel 40Cr medium carbon steel	P_{31}=7.80 g/cm^3 P_{32}=7.85 g/cm^3	c_{31}=3,982.00Yuan/t c_{32}=4,132.00Yuan/t	A_3=6.03 kg (four pieces)
Part IV	Common steel	P_{41}=7.80 g/cm^3	c_{41}=4,000.00Yuan/t	A_4=52.55 kg (one piece)

Table 8 The integrated evaluation results of each part

Parts	The synthetical value of potential impact to environment	ER-LCC of raw material extraction process, production process, use process, final disposal process (unit: Yuan)
Part I	$Y_1{}^0$=113.90	$C_{11}{}^0$=74.10, $C_{12}{}^0$=2.60, $C_{13}{}^0$=431.00, $C_{14}{}^0$=0.04
Part II	$Y_2{}^0$=2,732.80	$C_{21}{}^0$=1,178.41, $C_{22}{}^0$=61.82, $C_{23}{}^0$=10,344.40, $C_{24}{}^0$=0.92
Part III	$Y_3{}^0$=303.60	$C_{31}{}^0$=197.60, $C_{32}{}^0$=6.91, $C_{33}{}^0$=1,149.40, $C_{34}{}^0$=0.10
Part IV	$Y_4{}^0$=645.20	$C_{41}{}^0$=419.91, $C_{42}{}^0$=14.60, $C_{43}{}^0$=2,442.40, $C_{44}{}^0$=0.22

$$B_{11\times1}=\begin{bmatrix}1&1&1&1&1&1&1&1&1&1&1\end{bmatrix}^T$$
$$B_{3\times1}=\begin{bmatrix}1&1&1\end{bmatrix}^T$$

All of the above matrixes are substituted into Eq. (1). Discounted cost of each lifecycle process is obtained. The integrated inventory data is shown in Table 4.

5.3 Integrated impact assessment

Based on SETAC environmental classification standard, the main environmental impact of diesel engine is categorized into global warming, photochemical oxidant formation, acidification, and solid waste. The economic impact is categorized into raw material extraction process cost, production process cost, use process cost, and final disposal process cost. In the environmental characterization step, CO_2,NO_X,SO_2 are taken as the equivalency factors for global warming, photochemical oxidant formation, acidification. The potential contribution to each environmental impact category is obtained. The ER-LCC of each life process shown in Table 4 is the result of economic characterization. Environmental impact categories are normalized by a common scale, $\mathrm{mPET_{wcn2010}}$ (milli person equivalents, targeted for the World/China in year 2010). The weights (λ_i) for environmental and economic indices are identified by AHP according to the four-layer impact assessment index system. Then the environmental weight is $\omega1=\lambda5+\lambda6+\lambda7+\lambda8$, and the economic weight is $\omega2=\lambda1+\lambda2+\lambda3+\lambda 4$.All of the above results are listed in Table 5.

Based on the converting design index method introduced in this paper, the integrated benefit index $I_{\text{integration}}=0.86$, which is a comparable parameter used to making decision in choosing a better design. This index is the lower, which is the better.

Table 9 The weight of ER-C of life process of each part

Phases	The weights of ER-LCC of phases
Raw material extraction	$w_{11}=w_{21}=w_{31}=w_{41}=0.36$
Production	$w_{12}=w_{22}=w_{32}=w_{42}=0.08$
Use	$w_{13}=w_{23}=w_{33}=w_{43}=0.54$
Final disposal	$w_{14}=w_{24}=w_{34}=w_{44}=0.02$

After multiplying the potential contribution of each impact category with relevant weight, all the valuation results are illustrated in Fig. 5–6.

5.4 Interpretations

Some conclusions and recommendations can be induced from above integrated evaluation results:

- Global warming caused by CO_2, CO, and CH, is the main environmental impact category that impacts the environmental performance of diesel engine mostly.
- The cost of raw material extraction process and use process constitute the most important parts of ER-LCC of diesel engine. Therefore, environmental improvement in two life processes will have the most significant impact on the life cycle cost. The trade-off between environmental and economic performance in this two lifecycle processes is the key to increase integrated benefit.
- The environmental weight is much greater than the economic weight, which suggests that the environmental performance is more important than the economic performance now. Therefore, the diesel engine needs environmental improvement more even to sacrifice the economic benefit partly.

5.5 Optimization based on CSSO/NN

1. Premise
   - (a) The structure parameters of diesel engine in initial design are listed in Table 6.
   - (b) The weight and optional raw material types of each part in initial design are listed as Table 7. The raw material types of parts in initial design are all common steel, i.e., $P_1{}^0=P_2{}^0=P_3{}^0=P_4{}^0=7.80\mathrm{g/cm^3}$, $c_1{}^0=c_2{}^0=c_3{}^0=c_4{}^0=4,000.00\,\mathrm{Yuan/t}$.
   - (c) The integrated evaluation results of each part as the intermediate results of evaluation of the whole product are listed directly as Table 8.

Table 10 Optimization results

Design variables	Part I	Part II	Part III		Part IV	
Structure parameters (unit: cm)	Stroke	Diameter	Diameter	Length	Diameter	Length
	157.63	130.06	95.64	105.68	103.54	43.25
Raw material type	Al–Cu–Ni–Mg multi-components	Aluminum alloy	40Cr medium carbon steel		Common steel	

(d) w_{ij} indicates the weight of cost of each lifecycle process j of part i, showed in Table 9.

The weights of environmental and economic performance of the whole product are λ_1=0.61 and λ_2=0.39.

2. Optimization model

The length parameters and diameter parameters which impact the environmental and economic performance mostly are chosen as the design variables to validate the optimization method. The constraints of optimization model are identified according to the performance and structure requirements of type 4135G diesel engine.

s.t.

$$V_k = 225 \times \frac{N_e \cdot \tau}{P_e \cdot n \cdot i} = \frac{\pi}{4} X_1 \cdot X_2{}^2 \cdot 10^{-6}\text{liter} = 8\text{liter}$$

$$\frac{X_1}{X_2} - 1.3 \le 0, \quad 0.9 - \frac{X_1}{X_2} \le 0, \quad \frac{X_5}{X_2} - 0.85 \le 0, \quad 0.72 - \frac{X_5}{X_2} \le 0$$

$$\frac{X_6}{X_5} - 0.5 \le 0, \quad 0.45 - \frac{X_6}{X_5} \le 0, \quad \frac{X_3}{X_2} - 0.72 \le 0, \quad 0.64 - \frac{X_3}{X_2} \le 0$$

$$\frac{X_4}{X_2} - 0.87 \le 0, \quad 0.42 - \frac{X_4}{X_2} \le 0$$

Where P_e indicates the mean effective pressure, i is the number of cylinder, V_h indicates the working volume of one cylinder, liter, n indicates the crankshaft speed, τ indicates the number of stroke.

3. Optimization results

The data above is substituted into the optimization model. In terms of the GA, the optimization results are listed in Tables 10 and 11.

Optimal structure parameters and combined scheme of raw material are obtained by optimization algorithm. Environmental and economic burden have been decreased to the greatest extent so that the integrated benefit is maximized.

6 Conclusions

Through integrated evaluation, the important trade-offs between the economic and environmental performances are characterized, and the integrated performance is also obtained. Based on the integration, the optimization method brings the synthetic result to support the decision making in choosing or improving mechanical product design.

The result shows that the methods of integration and optimization are reasonable and feasible. The discrepancies in time dimension and system boundary are not insurmountable. After integrated assessment, the optimization of environmental and economic performance is also necessary for decision making of product design. Optimization algorithm based CSSO/NN can make the integrated benefit maximize by using the integrated evaluation results and optimization model.

However, there are limitations that need further research:

- The uncertainty of inventory data is not considered during the integration of inventory analysis;
- Weighting methods is not objective enough that lead to the uncertainty of integrated evaluation results.
- The optimization model has not established the relationship between chemical properties of raw material, technological process, and environmental performance. The effects of them to environment have not been quantified.

Table 11 The comparison of optimized design and initial design

Results	Initial design				Optimized design				Improvement degree
	Part I	Part II	Part III	Part IV	Part I	Part II	Part III	Part IV	
Weighted results of environmental burden (unit: mPET$_{\mathrm{wcn2010}}$)	113.90	2,732.80	303.60	645.20	148.56	2,443.87	352.84	603.60	10.70 %
Environmental burden of product	$Y = \sum_{i=1}^{4} Q_i Y_i = 2,121.60$				$Y = \sum_{i=1}^{4} Q_i Y_i = 1,894.90$				
Weighted results of economic burden (unit: Yuan)	507.74	11,585.55	1,354.61	2,877.13	425.94	11,611.6	1,442.94	2,056.9	−1.30 %
Economic burden of product	$C = \sum_{i=1}^{4} Q_i C_i = 8,954.24$				$C = \sum_{i=1}^{4} Q_i C_i = 8,838.20$				
Integrated benefit index	$I_{\mathrm{int\ egration}} = 0.86$				$I_{\mathrm{int\ egration}} = 0.73$				15.12 %

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