# Economic and Environmental Impacts of Product Service Lifetime: A Life-Cycle Perspective

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**Abstract.** This paper presents a generic model for evaluating the economic and environmental impacts of product service lifetime, which is important and useful in the design and management of PSS. From a PSS provider's perspective, the presented model conducts life-cycle costing (LCC) and life-cycle assessment (LCA) simultaneously and quantifies the total life-cycle cost and environmental impact associated with the product lifetime. The entire life cycle of the product is considered, including its manufacturing (or purchase), usage, maintenance, and end-of-life treatment. Applied with a sensitivity analysis of varying product lifetime, the model can identify the optimal service lifetime at which the life-cycle cost and environmental impact can be minimized. To illustrate, the developed model is applied to the example of a piece of currently-marketed agricultural machinery.

**Keywords:** Product life cycle, life-cycle costing (LCC), life-cycle assessment (LCA), product lifetime planning, optimal equipment replacement.

## 1 Introduction

As awareness and concern for environmental issues increase, business and government are faced with the key challenge of determining how best to promote and facilitate sustainable production and consumption. Products must be designed and manufactured carefully so that the entire lifecycle of a product (i.e., manufacturing, usage, maintenance, and end-of-life treatment) satisfies customers' needs while minimizing adverse environmental impacts. Product service system (PSS) can be a promising solution to this challenge. By selling functions instead of physical products, a PSS can satisfy customers' needs while reducing adverse environmental impacts [1].

This paper highlights the importance of a product's lifetime (i.e., the length of service) in the design and management of PSS. From a PSS provider's perspective, product service lifetime (hereinafter referred to as product lifetime) is an important factor that influences the total cost and environmental performance of their business.

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To maximize the economic and environmental sustainability of a PSS, it is critical to understand the impact of product lifetime. This paper presents a generic model that can be used to evaluate product lifetime. Life-cycle costing (LCC) and life-cycle assessment (LCA) are conducted simultaneously to evaluate the economic and environmental consequences of product lifetime. To illustrate, the developed model is applied to an example of currently-marketed agricultural machinery.

The remainder of the paper is organized as follows. Sections 2 and 3 describe the models for life-cycle costing and life-cycle assessment, respectively. Section 4 presents an illustrative case study with the example of an agricultural machine. Section 5 provides a summary of the study and concludes the paper.

## 2 Life-Cycle Costing

### 2.1 Overview

Life-cycle costing (LCC) is a technique for calculating the total costs related to a product and its entire life cycle. The life cycle of a product can be divided into four stages, i.e., manufacturing (or purchase), usage, maintenance, and end-of-life treatment. This section presents an LCC approach to calculating costs associated with the four life-cycle stages. The approach also incorporates costs for taxes, insurance and storage. Equation (1) provides the total life-cycle cost, $C^{total}$, under consideration:

$$C^{total} = C^{mfg} + C^{usage} + C^{maint} + C^{eol} + C^{tis} + C^{it} \quad (1)$$

where $C^{mfg}$, $C^{usage}$, $C^{maint}$, and $C^{eol}$ denote the costs of manufacturing, usage, maintenance, and end-of-life treatment, respectively, $C^{tis}$ denotes the costs for property taxes, insurance, and storage (TIS), and $C^{it}$ denotes the income tax effects.

The cost models in this paper provide the total and per-hour costs of product life cycle, given a specific product lifetime, *TY* (in years). Time value of money is considered in all models. More specifically, the models first calculate present equivalent of the total cost, and convert it into a series of equivalent uniform annual costs occurring at the end of each year for *TY* years. The capital recovery factor $i/[1-(1+i)^{-TY}]$ is used for the computation [2]. (See Equation (2) for example.) The resulting annual cost is then divided by the annual hours of product usage, *AH* (in hours), to obtain the hourly cost of the product (e.g., Equation (3)). In this paper, annual compounding with the real interest *i%* is applied, and the year-end occurrence is assumed for all costs—all cash flows associated with the year occur at the end of the year.

### 2.2 Manufacturing (Purchase)

The cost occurring at this stage is the manufacturing cost or the purchase expense. Suppose that the total cost at this stage is $C^{mfg}$. Since the product is acquired at time zero, there is no need to consider time value.

Equation (2) finds the uniform annual cost, $AC^{mfg}$, occurring at the end of each year that would be equivalent to the present cost $C^{mfg}$. Finally, Equation (3) gives the hourly cost of manufacturing, $HC^{mfg}$, by dividing $AC^{mfg}$ by $AH$.

$$AC^{mfg} = C^{mfg} \cdot \left[ \frac{i(1+i)^{TY}}{(1+i)^{TY} - 1} \right] \tag{2}$$

$$HC^{mfg} = AC^{mfg} / AH \tag{3}$$

## 2.3 Usage

Product usage generally involves the costs of energy consumption, such as cost of fuel, gas, or electricity. Suppose that a product consumes fuel for its operation, and the average fuel consumption rate (i.e., the amount of fuel consumed for an hour of operation) is estimated as $FR$ (in kg fuel/hour). Equation (4) then calculates the per-hour cost of usage by multiplying $FR$ by the unit price of fuel (i.e., $c^{fuel}$). It is also possible to compute the total usage cost, $C^{usage}$ (in present value), as shown in Equation (5). First, the uniform annual cost, $AC^{usage}$, is obtained by multiplying $HC^{usage}$ by the annual hours of product usage, $AH$. For each annual cost, its present equivalent is obtained considering the timing of its occurrence, and all the resulting present equivalents are summed up to the total usage cost, $C^{usage}$.

$$HC^{usage} = c^{fuel} \cdot FR \tag{4}$$

$$C^{usage} = \sum_{N=1}^{TY} AC^{usage} (1+i)^{-N} = \frac{AC^{usage}}{i} \cdot \left[ 1 - \frac{1}{(1+i)^{TY}} \right] \tag{5}$$

$$\text{where } AC^{usage} = HC^{usage} \cdot AH$$

## 2.4 Maintenance

Maintenance activities, i.e., the replacement of parts and lubricants, are another factor that affects the life-cycle cost of a product. To capture the cost of maintenance, one should know the number of replacements during the life cycle, the unit cost of each replacement, and the timing of cash flow for each replacement.

Equation (6) computes the total number of replacements of part $k$ during $TY$ years, i.e., $RN_k$, where $\lambda_k$ denotes the replacement cycle of part $k$ (in hours), and $TH$ refers to the total product lifetime (in hours), i.e., total accumulated hours of usage during $TY$ years. In Equation (6), the first replacement cycle is subtracted from $TH$, since the first part is included in a new machine and does not constitute a replacement.

$$RN_k = \left\lceil \frac{\max(0, TH - \lambda_k)}{\lambda_k} \right\rceil \quad \text{where } TH = AH \cdot TY \tag{6}$$

$$C^{maint} = \sum_{k \in K} \sum_{M=1}^{RN_k} c_k^{maint} \cdot \mu_k \cdot (1+i)^{-\lceil \lambda_k M / AH \rceil} \tag{7}$$

Equation (7) computes $C^{maint}$, the present equivalent of the total maintenance cost. Here, $\mu_k$ denotes the number of units of part $k$ in the product, and $e_k^{maint}$ denotes the per-unit cost (or purchase price) of replacement part $k$. Since all cash flows occur at the end of years, it must be identified for each replacement when it happens, in other words, what year the cost should be assigned to. The exponent using ceiling function is developed for this purpose. Similar to Equations (2) and (3), the total cost of maintenance can be converted into its equivalent costs per year and per hour. The same capital recovery factor and $AH$ are used for the calculation.

### 2.5 End-of-Life Treatment

The end-of-life phase involves activities such as third-party resale, recycling and disposal. It incorporates processing of the used product and all the waste from its maintenance (i.e., replaced part $k$). The product is sold for the salvage value of $c_{prod}^{eol}$, while the waste is processed with the unit cost of $c_k^{eol}$. Equation (8) computes the total cost of end-of-life treatment in its present equivalent. The total cost of end-of-life treatment can be converted into its equivalent costs per year and per hour, using the capital recovery factor.

$$C^{eol} = c_{prod}^{eol} \cdot (1+i)^{-TY} + \sum_{k \in K} \sum_{M=1}^{RN_k} c_k^{eol} \cdot \mu_k \cdot (1+i)^{-\lceil \lambda_k M / AH \rceil} \tag{8}$$

### 2.6 Property Tax, Insurance, and Storage

Taxes (property taxes, not income taxes), insurance, and storage (TIS) are another cost component due to product ownership. This paper assumes that this cost of TIS is paid at the end of each and every year, and that it equals to a fixed rate (i.e., $\alpha$) of the market value of a product, $mv_N$, that may depreciate over time [3].

$$C^{tis} = \sum_{N=1}^{TY} \alpha \cdot mv_N \cdot (1+i)^{-N} \tag{9}$$

### 2.7 Income Tax Effects

This paper considers three income tax effects, i.e., tax savings from depreciation, $c_1^{it}$, tax deductions due to deductible expenses, $c_2^{it}$, and the income tax related to product resale at the end of year $TY$, $c_3^{it}$ [4]. The sum of all three components gives the total income tax effect over the lifetime, $C^{it}$.

$$C_1^{it} = -\sum_{N=1}^{TY} \gamma \cdot \beta_N \cdot C^{mfg} \cdot (1+i)^{-N} \tag{10}$$

The value of product depreciates over time. The depreciation can be regarded as expense, which in turn reduces the income taxes. Equation (10) quantifies the total tax saving from product depreciation. The total saving has negative value since it reduces costs. The effective income tax rate is given as $\gamma$. The annual tax in year $N$ is determined by the depreciation rate of the year, $\beta_N$. The depreciation rates are defined by the tax law, and the sum of all depreciation rates over time reaches up to one; they are unconnected to the depreciation of market value.

Equation (11) computes the total tax deductions over the lifetime. The expenses at the usage and maintenance stages are assumed tax deductible [5]. Since time value was already considered in $C^{usage}$ and $C^{maint}$, there is no need to discount the value.

$$C_2^{it} = -\gamma \cdot (C^{usage} + C^{maint}) \tag{11}$$

Equation (12) calculates the income tax for the gain or loss at the end-of-life stage. When the used product is sold to a third-party at the end of year $TY$, the differences between its salvage value, $c_{prod}^{eol}$, (i.e., the actual selling price at the end of year $TY$) and the book value (i.e., value assessed based on the tax law and the depreciation rates, $\beta_N$) determines the tax amount.

$$C_3^{it} = \gamma \cdot (c_{prod}^{eol} - C^{mfg} \cdot \sum_{N=1}^{TY} \beta_N) \cdot (1+i)^{-TY} \tag{12}$$

# 3 Life-Cycle Assessment

## 3.1 Overview

Life-cycle assessment (LCA) is an essential tool for achieving design for life cycle. LCA evaluates the potential environmental impact associated with a system (i.e., a product, a service, or a PSS), considering its entire life cycle. As shown in many previous studies (e.g., [6, 7]), an effective LCA can demonstrate how much environmental impact is caused by a system and how different life-cycle phases and/or subsystems contribute to the total impact. The results of the LCA help identify priority areas for improvement and ways to reduce environmental impacts.

$$I^{total} = I^{mfg} + I^{usage} + I^{maint} + I^{eol} \tag{13}$$

Equation (13) computes the total life-cycle impact of a product, $I^{total}$. Here, $I^{mfg}$, $I^{usage}$, $I^{maint}$, and $I^{eol}$ denote the impacts of manufacturing, usage, maintenance, and end-of-life treatment, respectively. It should be noted that the environmental impacts has no time value, unlike the life-cycle costs in Section 2. In the remainder of the section, it is discussed how to assess the impact of each life-cycle stage. Given specific product lifetime $TY$, the models calculate the total environmental impact; the hourly impact is then obtained by dividing the total impact by $TH$ (= $AH \cdot TY$).

### 3.2 Manufacturing

The impact of manufacturing is determined by the design of a product. More precisely, it is defined by the material composition and manufacturing processes of the product. Transportation is also included. The mass, travel distance, and transportation mode (e.g., truck, oceanic freight shipping) determine the impact of transportation.

Equation (14) computes the impact of manufacturing, where $e_r^{matl}, e_p^{mproc}$, and $e_q^{tproc}$ denote the per-unit impacts of raw material $r$ ($r \in R$), manufacturing process $p$ ($p \in P$), and transportation mode $q$ ($q \in Q$), respectively; $x_r$, $x_p$, and $x_q$ denote the total number of units of material $r$, manufacturing process $p$, and transportation mode $q$, respectively, that are used in manufacturing the product.

$$I^{mfg} = \sum_{r \in R} e_r^{matl} \cdot x_r + \sum_{p \in P} e_p^{mproc} \cdot x_p + \sum_{q \in Q} e_q^{tproc} \cdot x_q \tag{14}$$

### 3.3 Usage

The impact of usage can be divided into the impact of energy consumption and the impact of emissions. For the product using fuel for its operation, the former includes the impacts from producing and delivering fuel. The latter focuses on the emissions from diesel fuel combustion, such as carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), carbon monoxide (CO), and particulate matter (PM).

Equation (15) formulates the environmental impact of fuel consumption, $I^{fuel}$. In the equation, $e^{fuel}$, $FR$, and $TH$ denote the unit impact of fuel (i.e., impact per kg fuel), the average fuel consumption rate (in kg/hr), and the total product lifetime in hours, respectively. Equation (16) formulates the impact of emissions, where $e_l^{emission}$ and $ER_l$ denote the unit environmental impact (impact per kg of emission) and the average emission rate (in kg/hr) of emission $j$, respectively.

$$I^{fuel} = e^{fuel} \cdot FR \cdot TH \tag{15}$$

$$I^{emission} = \sum_{l \in L} \left( e_l^{emission} \cdot ER_l \cdot TH \right) \tag{16}$$

### 3.4 Maintenance

Equation (17) computes the impact of maintenance, where $e_k^{maint}$ denotes the per-unit impact of a replacement part $k$. As described in Section 2.4, $\mu_k$ denotes the number of units of part $k$ in the product, $RN_k$ denotes the total number of replacements of part $k$ over the lifetime $TH$, and $\lambda_k$ denotes the replacement cycle of part $k$ in hours. Again, the first replacement cycle is subtracted from $TH$, since the impact of the first replacement was already counted at the manufacturing stage.

$$I^{maint} = \sum_{k \in K} \mu_k \cdot RN_k \cdot e_k^{maint} = \sum_{k \in K} \mu_k \cdot \left\lceil \frac{\max(0, TH - \lambda_k)}{\lambda_k} \right\rceil \cdot e_k^{maint} \tag{17}$$

### 3.5 End-of-Life Treatment

The impact of end-of-life treatment includes both the impacts of processing the end-of-life machine and processing all replacement parts and fluids consumed over the life cycle. Equation (18) provides the impact of end-of-life treatment, where $e_{prod}^{eol}$ and $e_k^{eol}$ denote the unit environmental impacts of used product and used part *k*, respectively. As described in Section 2.5, the used product is assumed to be sold to a third-party at the end of year *TY*. Thus, its impact may include the impact of delivering the product to the third-party. The unit impact of used part *k* includes both the impact of its transportation to the treatment facility and the impact of its recycling and/or disposal.

$$I^{eol} = e_{prod}^{eol} + \sum_{k \in K} \mu_k \cdot \left\lceil \frac{\max(0, TH - \lambda_k)}{\lambda_k} \right\rceil \cdot e_k^{eol} \tag{18}$$

## 4 Illustrative Case Study: Agricultural Machinery

### 4.1 Background

To illustrate the developed model, a case study of an agricultural harvester is presented in this section. The target machine is characterized by a complex product structure with a large number of constituent parts, and it has high fuel consumption throughout its long lifetime. Throughout its lifetime, the machine is assumed to be used following a constant usage pattern: 400 hours of operation per year (i.e., *AH* = 400) with 75% of the time spent for actual production (25% idling).

Suppose there is a company planning a PSS business with the target machine. The company aims to find the optimal machine lifetime *TY** (in years) whereby the total life-cycle cost and environmental impact of the machine would be minimized. In this study, 9% real interest rate was assumed based on the company's after-tax weighted average cost of capital (WACC) [2]. Regarding the income tax, the effective tax rate was assumed to be 25%. The trend of book values is assumed following the 7-year MACRS (Modified Accelerated Cost-Recovery System) depreciation rule; for the first seven years, the depreciation rates are 10.71, 19.13, 15.03, 12.25, 12.25, 12.25, 12.25, and 6.13%, respectively [5]. Afterwards, the depreciation rates are zero. Figure 1 shows the depreciation trend of the target machine.

In this case study, global warming potential (GWP) was used as the measure of environmental impact, even though the model generally is applicable with any other impact metrics as well, such as an Eco-Indicator 99 score. LCA software SimaPro 7.3 and life-cycle impact assessment (LCIA) method IPCC 2007 were used for the impact assessment. IPCC 2007 quantifies the GWP of product life cycle considering greenhouse gas emissions for a fixed time period (in this study, 100 years). The unit of GWP is kg $CO_2$ equivalent (kg $CO_2$e).

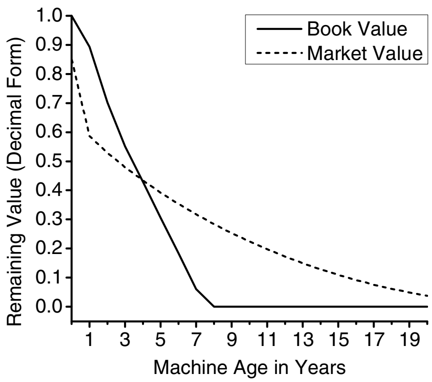


**Fig. 1.** Value depreciation assumed for the target machine [3, 5]

**Table 1.** Assumptions on maintenance: major parts replacement

| Part | Replacement cycle | Replacement cost |
|---|---|---|
| Tires (6 units) | 3000 hours | $12,400 |
| Engine | 5000 hours | $42,700 |
| Transmission | 3000 hours | $38,700 |
| Hydraulic components | 3000 hours | $45,500 |
| Axles | 5000 hours | $9,600 |

**Table 2.** Fuel consumption (kg/hr) and emission rates (g/hr) assumed for the target machine

| Type | Nonidling | Idling | Average |
|---|---|---|---|
| Diesel fuel | 47.07 | 21.37 | 40.65 |
| Nitrogen oxides ($NO_x$) | 372.73 | 143.16 | 315.34 |
| Particulate matter (PM) | 1.76 | 0.67 | 1.49 |
| Carbon monoxide (CO) | 23.84 | 9.16 | 20.17 |
| Hydrocarbons (HC) | 5.42 | 2.08 | 4.59 |
| Sulfur dioxide ($SO_2$) | 0.99 | 0.45 | 0.86 |
| Carbon dioxide ($CO_2$) | 149627.50 | 67944.69 | 129206.80 |

**Purchase and TIS.** The weight of the target machine is approximately 23,000 kg, and more than 16,000 parts are used in its manufacturing. The machine consists mostly of steel and cast iron (approximately 90%). Rubber and plastics are the second and third prevalent materials. The price and environmental impact (impact of manufacturing only) of a new machine were assumed to be $350,000 and 83,000 kg $CO_2$e. The market value depreciates over time, and the cost of TIS (i.e., property tax, insurance, and storage costs) also decreases accordingly. In this study, the depreciation model from Ref. [3] was adopted for the market value estimation. The model estimates the market value trend of a machine by considering its age and the annual hours of usage. It gives the market value at the end of each year. Figure 2 shows the market value trend assumed for the target machine. Finally, the TIS rate was assumed to be 2% in total (i.e., $\alpha = 0.02$).

**Maintenance.** The type and frequency of maintenance activities were assumed based on the average maintenance schedule recommended by the equipment's manufacturer. Table 1 shows some of the assumptions relative to the replacement of major parts. It was assumed that the first major rebuilding will occur at 3,000 hours (in year 8) and that the engine will be replaced at 5,000 hours (in year 13). Minor parts, oil, filters, and fluids also were replaced following its own maintenance schedule. The costs per replacement were assumed based on the manufacturer's parts catalog.

For simplicity, this study assumed that the major repairs and overhauls do not affect the book value or the market value of the machine. However, if they require adjustments of the values, a more sophisticated approach may need to be applied in assuming value depreciation in Figure 2 [4].

**Usage.** The use phase of the target machine involves two impact sources: diesel fuel consumption and emissions. Table 2 shows the fuel consumption (in kg/hr) and emission rates (in g/hr) assumed for the target machine. The density and cost of diesel fuel were assumed as 0.855 kg/liter and $1.08/kg (= $3.5/gallon), respectively.

**End-of-Life Treatment.** At the end-of-life stage, the machine is sold to a third-party. The salvage value was assumed to be identical with the market value of the machine. Zero environmental impact was assigned in case of the third-party resale.

All waste from maintenance is either recycled or discarded. In terms of weight, 90% of steel and iron is recycled while the rest 10% is discarded by landfill. The other materials are discarded either by landfill (80%) or incineration (20%). The processing cost was assumed as $40 per metric ton. For allocation of environmental impact, the "cut-off approach" was applied. In other words, the environmental impacts or benefits from recycling were not allocated to the current life cycle [8, 9].

### 4.2 Evaluation Result: Implications of Product Service Lifetime

The stacked column charts in Figures 2 and 3 present the results of life-cycle costing and life-cycle assessment, respectively. Per-hour values are illustrated for various lengths of product lifetime from 1 to 20 years.

**Life-Cycle Cost.** Figure 2 shows the per-hour cost of product life cycle with different lengths of service lifetime. Each stacked column shows how the eight cost components (i.e., four life-cycle stages, TIS, and income tax effects) contribute to the total cost for the given product lifetime. A negative value indicates that the cost component saves taxes or recovers some costs (e.g., end-of-life stage recovers the purchase expense of the machine).

Figure 2 shows how the per-hour life-cycle cost would change with the lifetime of the machine, *TY*. Basically, the per-hour cost in the black line shows a decreasing trend with the age of the machine. This is due mainly to the reduced cost of manufacturing; the more years a machine is used, the more hours there are to spread the cost of manufacturing over. However, as the lifetime increases more, the benefit of longer lifetime is sometimes offset by the increasing cost of maintenance. Although maintenance expenses accompany some income tax savings, they become one of the most expensive components with the age of the machine. Especially, the major rebuilding and parts replacements create significant rise in the total cost, especially in year 8, year 13, and year 16.

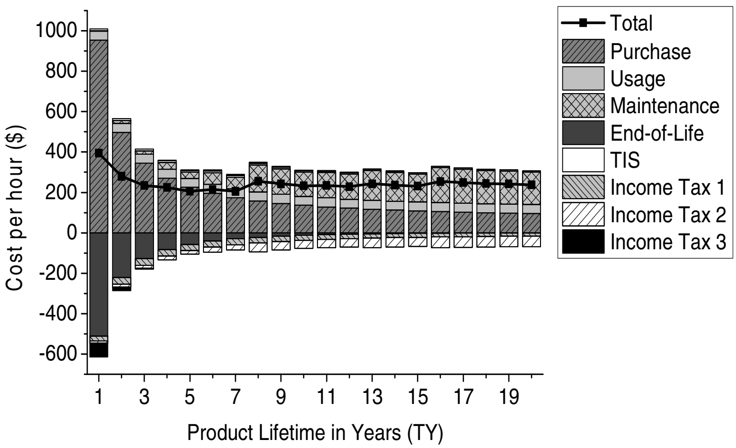


**Fig. 2.** Per-hour costs of product life cycle varying for different lifetime lengths

A trade-off also exists between the costs of end-of-life stage and TIS. Since the market value of the machine depreciates with machine age, the longer lifetime implies the less salvage value at the end of life stage. However, the depreciation can help save TIS (and sometimes income taxes, as well).

**Life-Cycle Impact.** Figure 3 shows the results of the environmental impact assessment with various years of machine lifetime. All impacts are for an hour of operation. Each column in the figure shows the amount and contribution of the global warming potential impact associated with different life-cycle phases. The overall trend of the per-hour impact is similar to that of per-hour cost. The per-hour impact shows a decreasing trend with the age of the machine due to the reduced impact of manufacturing. However, the major rebuilding and parts replacements sometimes cause some increases in the per-hour impact.

**Implication of Product Lifetime.** One major difference to note for Figure 3 is that, the usage stage is the main contributor for the total environmental impact, and the maintenance stage is less emphasized. Accordingly, the influence of maintenance is not much significant in Figure 3. Such difference leads to different consequences for the same product lifetime. Figure 4(a) compares the trends of per-hour cost and per-hour impact for the same range of product lifetime from 1 to 20 years. When $TY = 8$, 13, and 16 – the years of machine rebuilding and major parts replacement, both the

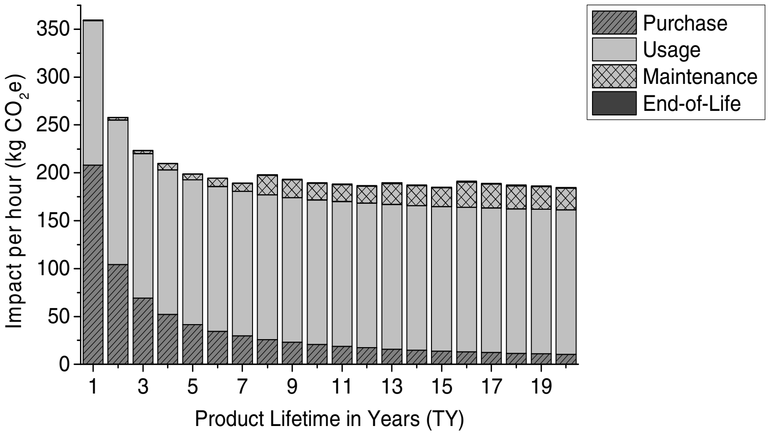


**Fig. 3.** Per-hour impacts of product life cycle varying for different lifetime lengths

cost and impact show the same increasing trends. However, the degree of increase in per-hour impact is marginal compared to the degree shown in per-hour cost.

Figure 4(b) compares different lengths of product lifetime using a two dimensional map. The x-axis represents the per-hour cost, and the y-axis represents the per-hour environmental impact. As highlighted in the figure (red circles), four lifetime lengths were revealed as Pareto optimal alternatives. These are *TY* = 7, 12, 15, and 20 years. The lifetime with the minimum cost is 7 years, while the lifetime with the minimum environmental impact is 20 years.

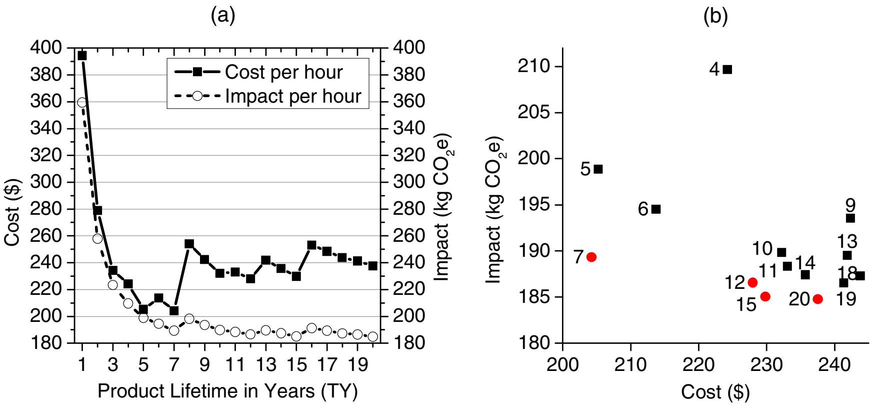


**Fig. 4.** Implications of product service lifetime: (a) Trends in economic and environmental consequences, (b) Pareto optimal for service lifetime (data label: product lifetime in years)

## 5 Discussion

To minimize costs and environmental impacts associated with a PSS, it is important to carefully set the product lifetime. Understanding the economic and environmental impacts of product lifetime is critical in this regard. This paper presents a generic model that can be used to evaluate the service lifetime of a product.

The model consists of two parts, i.e., life-cycle costing (LCC) and life-cycle assessment (LCA), which simultaneously evaluate the economic and environmental impacts of product service lifetime. The model considers the entire life cycle of a product, including its manufacturing (or purchase), usage, maintenance, and end-of-life treatment. Important economic factors, such as time value of money, taxes, and value depreciation, were also taken into account. Applied with a sensitivity analysis of varying product lifetime, the model can identify the service lifetime at which the life-cycle cost and environmental impact can be minimized. The developed model was demonstrated with a currently-marketed agricultural harvester.

In the future, sensitivity analyses will be conducted to clarify how various parameters and variables affect the economic and environmental impacts of product lifetime. Optimal product lifetime is also affected by improvement in the performance of new products [10]. In future research, the current model, which only considers a single product, should be extended to a more sophisticated model that could consider multiple generations of products with significant technological changes.

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