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Treatise on Sustainability Science and Engineering

Springer

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Preface

"Treatise on Sustainability Science and Engineering" is aimed at bringing out the state-of-the-art developments in sustainability applications, including principles and practices developed and implemented across a wide spectrum of industry. This book presents a total of 18 chapters, authored by prominent researchers and application specialists in sustainability science and engineering, and these chapters are thematically assembled in the following four major parts:

Part I: Design for Sustainability (6 Chapters)
Part II: Sustainability Metrics and Analysis (4 Chapters)
Part III: Sustainable Energy (5 Chapters)
Part IV: Sustainable Supply/Value Chains (3 Chapters)

Part I introduces design for sustainability concepts, methodologies, principles, and practices through systematic studies in a total of six closely related chapters covering a range of models and design and application methodologies for sustainability, beginning with a "Life-Cycle Optimization Methods for Enhancing the Sustainability of Design and Policy Decisions" outlining and presenting life cycle optimization methods.

LCO developed for evaluating the optimal service life and asset management decisions from energy, emissions, costs, and policy issues. This LCO model is based on dynamic programming methods. Applications are drawn from automobiles and the household refrigerators and air conditioners, with trade-offs between utilizing the existing product models and replacing it with the more efficient newer one. This is followed by "Second Thoughts on Preferred End-of-Life Treatment Strategies for Consumer Products" providing further thoughts on new, preferred end-of-life strategies for consumer products which have, typically, lifetime extensions as preferred options to disassembly options for reuse and recycling. This priority hierarchy method was shown as too simplistic in the light of new technological advances involving the use of self-disassembly methods and business propositions, with research-driven case studies demonstrating the reversal of such traditional priority end-of-life options by emphasizing the viability of systematic product reuse, refurbishment or disassembly for reuse where material recycling was shown as the only realistic scenario. "A New Methodology for Integration of End-of-Life Option Determination and Disassemblability Analysis" in this part presents a new methodology for integrating the process of end-of-life determination with product disassembly decision methods by introducing a five-stage strategy: (1) product definition, (2) determination of end-of-life option with residual value calculation, (3) evaluation of disassembly methods with relevant cost analysis, (4) calculation of recycling costs, and (5) documentation of a disassembly report. A case study is presented to demonstrate the feasibility of this new methodology. "Sustainability Under Severe Uncertainty: A Probability-Bounds-Analysis-Based Approach" deals with an introduction of a probability bound analysis (PBA) method for handling uncertainties due to lack of and/or imprecise information on sustainability. The use of this method was shown as feasible for modeling the propagation of uncertainty through complex mathematical models in simulation and decision making. This is shown through a study of two different computational algorithms: Dependency Bound Convolution (DBC) for simple algebraic formulations, and the Black-Box Compatible (BBC) methods for complex models. "Life Cycle Assessment (LCA): A Means to Optimise the Structure of Sustainable Industry" in this part shows the Life Cycle Assessment (LCA) method as a means to optimize the structure of the sustainable industry by showing that sustainability will influence all aspects of industrial processes including the raw material base, size, and location of their interactions within and with the environment, and with the economic and social implications. A case study of first generation bioethanol processes is demonstrated to highlight such interactions. The last chapter in this part "Practical Approaches to Sustainability: iSUSTAIN® Tool for Green Chemistry Case Study" introduces a Green Chemistry Scoring Tool iSUSTAIN™. This tool is based on the 12 principles of green chemistry where metrics were developed for each tool to measure the sustainability contents of products and processes in terms of their inherent "greenness".

Part II presents a detailed sustainability metrics and analysis in four chapters. "Measuring Sustainability: Deriving Metrics from a Secure Human–Environment Relationship" presents a practical means for measuring sustainability in terms of developed metrics with minimum human adverse effects. It is promoted that the newly defined metrics must define the boundaries of human activities relative to environmental capabilities to offer some early warning signs of such conditions that would normally be unfavorable to human life, thus leading to an imposed change. "Science-Based Metrics for Product Sustainability Assessment" makes an attempt to present a framework for developing science-based metrics for evaluating product sustainability.

This chapter shows the recent NIST efforts in addressing the need for developing such metrics and tools for scientific evaluation of life cycle economic and environmental performance of products. The latter is shown to be measured using LCA methods that assess the "carbon footprint" of products, as well as 11 other sustainability metrics including fossil fuel depletion, smog, water use, habitat alteration, indoor air quality, and human health. These performance metrics are applied in the assessment of 230 building products within the NIST's Building Environmental and Economic and Sustainability (BEES) tool involving a BEES case study of five floor covering products. "Key Business Metrics that Drive Sustainability into the Organization" presents key business metrics that drive sustainability into the organizations based on the stakeholder context from the sustainability-related aspirations, goals, and challenges that are both internal and external to an organization. This chapter also introduces the GEMI *Metrics Navigator*™ process, a roadmap for identifying key sustainability issues, and business metrics, which are aimed at achieving the sustainability goals of an organization. The next chapter in this part "Environmental Assessment and Strategic Environmental Map Based on Footprints Assessment" presents a novel graphical representation using an environmental evaluation and strategic environmental map based on the various footprints such as carbon footprint, water footprint, energy footprint, emission footprint, work environment footprint, etc. This graphical method allows the use of these footprints with an additional dimension of cost.

Part III integrates five interrelated chapters in the major area of sustainable energy. This part begins with a "Exploring How Technology Growth Limits Impact Optimal Carbon Dioxide Mitigation Pathways" showing how technology growth can limit impact optimal carbon dioxide (CO_2) mitigation pathways. In this chapter, alternative growth bounds on wind and solar power, nuclear power, and CO_2 sequestration are examined for a hypothetical greenhouse gas (GHG) mitigation scenario. A nested parametric sensitivity analysis is used to examine the response to individual and combinations of bounds. Both, modeling and planning perspectives are shown. "Nanoscale Engineering Approach for Enhancing the Performance of Photovoltaic Cell Technologies for Non-Fossil Energy Sources" presents a specific nanoscale engineering approach for enhancing the performance of photovoltaic (PV) cell technologies for the use of non-fossil energy sources. Two emerging technologies, PV cells and concentrated solar power (CSP) are shown as capable of delivering the large portion of United States' energy needs in the next 40 years if they are properly developed. In this chapter, first, fundamental mechanisms of how electricity is generated by these two technologies are described. Next, recent developments in the application of nanotechnology for enhancing PV cell performance are presented. This chapter shows a nanoscale engineering approach for developing device designs that would counter the two limiting factors. "Sustainable Mobility: Insights from a Global Energy Model" presents sustainable mobility insights from a global energy model that includes a detailed description of light-duty vehicle and fuel technologies, used to investigate cost-effective light-duty vehicle/fuel technologies in a carbon-constrained world. Three conclusions emerged from this chapter. First, there is no "silver bullet" vehicle or fuel technology. Second, a multisector perspective is needed when addressing greenhouse gas emissions. Third, alternative fuels are needed in response to the expected dwindling oil and natural gas supply potential by the end of the century. "Life-Cycle Analysis of Biofuels and Electricity for Transportation Use" presents a LCA of biofuels and electricity for transportation use. This chapter shows that the transportation sector has been relying solely on petroleum, consuming more than 50 % of the global world oil production, with the United States being the top oil-importer country. Two major issues facing the transportation sector in the U.S. and other major countries are shown: energy security and environmental sustainability. It was shown that improvements in the energy efficiency of vehicles and the substitution of petroleum fuels with alternative fuels can help to slow the growth in the demand for petroleum oil and mitigate the increase in greenhouse gas emissions. Biofuels and electricity are known for their potential reduction of petroleum use and greenhouse gas emissions. This chapter examines the potential reduction of life cycle energy use and greenhouse gas emissions associated with the use of biofuels in internal combustion engine vehicles and electricity in plug-in hybrid electric vehicles and battery-powered electric vehicles. The last chapter in this part "Liquid Biofuels: We Lose More Than We Win" shows a critical scenario where biomass, according to the world trends, is shown as a priority resource for fossil fuel substitution, and that biomass is increasingly used for both the transport and the heat and power sectors, with increasing interest in using it for chemical production as well. The chapter shows that as the magnitude of biomass, that is or can be made available for energy purposes, is small compared to the magnitude of the new potential customers for it, any long-term and large-scale prioritization of biomass for one purpose will imply a loss of alternative uses of the same biomass. If the lost alternatives are, then, significantly more efficient as well as economically more attractive in fossil fuels substitution and CO_2 reduction, we lose more than we win. The authors claim that this is the case for most liquid biofuels, including first generation biodiesels (plant biodiesels) as well as first and second generation bioethanols produced in Europe and the USA.

Part IV presents three interesting chapters on sustainable supply chains, with the opening chapter "Meeting the Challenge of Sustainable Supply Chain Management" showing that assessing and improving the sustainability of products and services requires a life cycle approach, consideration of the complete supply chain, and examination of the role of consumption as the driver for production. It is shown that the economic and environmental dimensions can be explored by integrating value chain analysis (VCA) and LCA to show the distribution of economic benefits and environmental impacts along the supply chain. Environmental intensities (i.e., impact per unit of added value) are shown as frequently high for material extraction and refining, and reduce progressively along the supply chain through manufacturing and distribution. Incorporating consideration of social equity in analysis of supply chains was shown to require further methodological development involving a "soft system" analysis to complement the "hard system" approaches of VCA and LCA. From the consumption perspective, it is shown that sustainable development requires not only reduction in the environmental intensity of products and services, but also more equitable distribution of economic and social benefits along the supply chain. "Sustainable Consumption and Production: Quality, Luxury and Supply Chain Equity" shows that the pressures of social and environmental responsibility require companies to consider sustainability issues across the full product life cycle, from the conduct of upstream suppliers to the disposition of obsolete products. In this regard, leading companies are shown to be adopting a variety of sustainable business practices that reduce their supply chain footprint while generating increased value for stakeholders. Systems thinking and life cycle management are shown as key elements in achieving measurable improvements in sustainability and profitability. The author shows that the incremental supply chain efficiency improvements are insufficient to slow the increases in carbon emissions and other adverse ecological impacts and collaboration is urged among progressive multinational companies with governments and nongovernmental organizations to enable decoupling of material flows from the economic value creation. "Transforming Supply Chains to Create Sustainable Value for All Stakeholders" presents the need for sustainable value creation by showing that promoting sustainability in business operations requires that products, processes as well as the entire supply chain (the system), is designed and operated by taking account of not only economic benefits, but also environmental and societal implications. The chapter presents that from a supply chain perspective, economic value added (EVA) has long been used as a measure to evaluate supply chain performance. This chapter presents the concept of sustainable value creation and why the scope of conventional supply chain management processes must be broadened to generate sustainable value. This chapter offers a discussion of successful and disastrous case examples.

Overall, the four parts of this proposed book-volume are filled with closely knitted, carefully chosen, and interacting 18 chapters of significant state-of-the-art work. All chapters have been peer-reviewed and revised accordingly. We sincerely thank all reviewers who carefully reviewed the chapters and provided valuable comments for revision. This edited book would add significant values to the readers in the domain of sustainability science and engineering. Researchers in academic and industrial organizations, technical and managerial staff from companies, and staff from governmental organization would benefit from the collection this work, which is aimed at advancing the current state-of-the-art into next level for greater societal benefits.

The authors and co-authors of all chapters deserve credit for their excellent contributions and timely actions on various aspects of the production of this book. We also sincerely thank the two graduate students at the University of Kentucky, Tao Lu and Chris Stovall for their hard work in carefully proofreading all finally updated chapters, and for working with all authors of chapters in completing documentation needed for the publication of this book. We also thank the publishers for their support and help in publishing this book.

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Contents

Part I
Design for Sustainability

Life-Cycle Optimization Methods for Enhancing the Sustainability of Design and Policy Decisions

Gregory A. Keoleian

Abstract A critical question regarding the life-cycle design and management of any product system is, "What is its optimal service life?" The Center for Sustainable Systems at the University of Michigan has developed life-cycle optimization (LCO) methods and models to evaluate optimal service life and asset management decisions from energy, emissions, cost, and policy perspectives. This LCO model is based on a dynamic programming method with inputs derived from life-cycle assessment and life-cycle cost analysis. From an environmental perspective, this is a particularly complex question to resolve for product systems with nonlinear use phase burdens and uncertain technology improvement trajectories. This chapter presents the basic LCO methodology and demonstrates its application to automobiles and household refrigerators. In both cases, there exist multiple tradeoffs between utilizing an existing product model and replacing it with one that is more efficient. The operational efficiency gain from model replacement should exceed the additional resource investments required to produce the new model. LCO simulations indicate that optimal replacement schedules are strongly influenced by technology improvement rates, product deterioration rates, production versus use phase impact ratios, and consumer use patterns. Results from replacement case studies of automobiles, refrigerators, air conditioners, and highway infrastructure will be highlighted and general principles for enhancing sustainability will be presented. Life-cycle optimization is expected to become another important technique to add to the life-cycle modeling toolkit for informing design and policy decisions.

Keywords LCA · Service life · Life-cycle cost · Life-cycle optimization

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1 Introduction

We retire and replace products for multiple reasons including technical obsolescence, fashion obsolescence, degraded performance or structural fatigue caused by normal wear over repeated use, environmental or chemical degradation, and damage caused by accidents or inappropriate use. A commonly held belief is that extending the service life of a product will always improve overall sustainability performance. By extending the life of the product, the manufacturing environmental burdens and costs of a new product are avoided or delayed and the impacts associated with product retirement can also be displaced. In simple terms, longer-lived products save resources and generate less waste, because fewer units are needed to provide that same length of service. This product life extension principle or strategy has been advocated by many environmentalists and is also reported in the academic literature. For example, several designs for environment or design for sustainability frameworks have included product life extension as a key strategy for reducing impacts (Stahel 1986; Keoleian and Menerey 1993, 1994; Anastas and Zimmerman 2003). Product life extension can be achieved through a variety of product design approaches such as enhanced durability, adaptability, reliability, remanufacturing, and reuse.

This principle is generally accurate for products that do not create impacts during the use phase. For example, manually operated garden tools such as a spade or rake should be designed for maximum service life and repair mechanisms such as replacing a handle will generally lead to lower impacts than complete product replacement. Optimal replacement policies for more complex energy-consuming products such as automobiles, appliances, electronics, buildings and infrastructure, and other systems that may also undergo rapid technological innovation require much more sophisticated analysis.

The need to rapidly transform our product systems for achieving sustainable development is well understood. The transition from old less sustainable to new more sustainable systems is critical for reducing material and energy consumption, greenhouse gas emissions, water consumption, and ecological and human health impacts. Dramatic improvements in use phase performance can outweigh impacts associated with manufacturing new products for replacement. The key parameter is the rate of improvement; otherwise without improvement life extension is a more effective strategy.

The life-cycle optimization (LCO) method was developed at the Center for Sustainable Systems through an NSF Technology for Sustainable Environment grant. This interdisciplinary research project combined expertise in industrial ecology with industrial and operations engineering. The idea for the research was initiated when I and a colleague (Jonathan Bulkley) asked the simple question to a new doctoral student (Hyung Chul Kim), “When should we retire our older automobiles?” The simple question, however, required an in-depth and complex treatment of the problem. The LCO method, which will be summarized in this chapter, was initially published (Kim et al. 2003). In addition to automobile replacement policy, this method has been applied to refrigerators (Horie 2004; Kim et al. 2006), clothes washers (Bole 2006), and most recently household air conditioners (De Kleine et al. 2010a, b).

The purpose of this chapter is to present the LCO methodology for guiding product design and replacement policy; demonstrate the LCO method with applications to automobiles and refrigerators; and conclude with some observations and recommendations about replacement policy. A brief overview of the relevant literature will be presented in the Background (Sect. 2) and the Objectives will be outlined in Sect. 3. A description of the LCO method and basic model equations is provided in the Methods and Applications (Sect. 4). The results from the application of the LCO method to automobiles and refrigerators are presented in Sect. 5. Based on these two case studies and LCO research of other systems, this chapter concludes with key findings and principles for guiding design and policy in Sect. 6.

2 Background

Life-cycle assessment (LCA) is the analytical tool for evaluating environmental sustainability performance of a product system (ISO 1998; Keoleian and Spitzley 2006). This assessment provides a comprehensive profile of the environmental burdens and impacts across materials production, manufacture, use, and retirement stages of a product system. Life-cycle cost analysis is a similar tool for measuring purchase, use and service, and disposition costs. These tools, however, are insufficient by themselves in examining issues of optimal service life or the timing for product repair, retirement, and replacement.

The literature for optimal product management decisions from an economic perspective is very well established in the industrial engineering and operations research literature. The treatment of optimal replacement policy and decisions from an environmental sustainability perspective has only been considered more recently. While retirement decisions are most often guided by economic considerations, the optimal product service life also poses a complex resource and environmental management problem. The basic tradeoff between keeping an existing product and replacing it with a new one to improve environmental performance is illustrated in Fig. 1 for an automobile. The older vehicle is shown on the left and is referred to as the *defender* in industrial engineering vernacular, and the *challenger* represents newer model vehicles. The initial capital and resource investment has been made for the existing vehicle but it is inefficient and more polluting than a newer model. Although the newer model is more efficient, the production of the new vehicle creates burdens and impacts.

In addition to the research of the Center for Sustainable Systems at the University of Michigan that will be highlighted in this chapter, a few other relevant research studies will be described briefly. The integration of optimization techniques in LCA was first applied by Azapagic and Clift (1999). They developed a life-cycle-based multi-objective optimization method for environmental management of a product system.

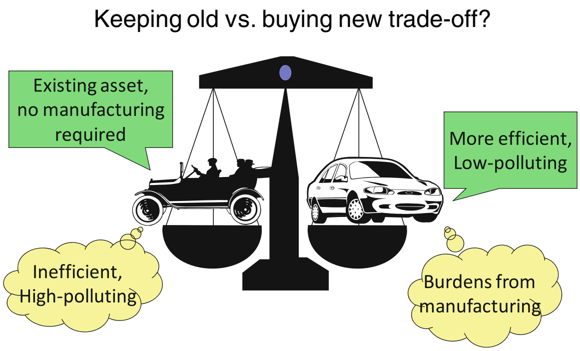

Fig. 1 Environmental tradeoff between an existing vehicle and a newer model

This technique was used to select an optimal set combination of chemical manufacturing processes with respect to multiple environmental and cost objectives. In this case study, the use and disposal phases of the products were not considered and therefore it can be classified as a "cradle-to-gate" study. While it did not address product replacement decisions, it likely represents the first application of optimization methods with LCA.

There are also several studies that have explored remanufacturing strategies using LCA. For example, Kerr and Ryan (2001) have studied remanufacturing of copier machines and Smith and Keoleian (2003) investigated remanufactured automobile engines. They compared remanufacturing strategies with new product replacement alternatives. These studies, however, did not utilize optimization methods.

Finally, Kagawa et al. (2006) investigated the environmental and economic consequences of product lifetime extension. They conducted an empirical analysis of automobile life extension. Although this was not an optimal replacement study, this macroeconomic analysis provided interesting findings regarding the impact of car lifetime extension on the environment and the domestic economy.

3 Objectives

The objectives of this chapter are to present the LCO method and demonstrate its application for guiding product replacement policy of two product systems, automobiles and household refrigerators.

These two different systems are analyzed and the results are contrasted. Both examine the optimal replacement policy over the 1985–2020 time horizon; one for an average mid-sized car and the other for a typical household refrigerator in the US. It is important to note that these studies were originally published in 2003 and 2004, respectively.

The replacement policies were developed based on different objectives (i.e., objective functions). The replacement schedules for the automobiles minimized

CO_2, NO_x, NMHC (non-methane hydrocarbons), CO, energy, and cost. For refrigerators, the replacement policies for optimizing energy, greenhouse gas emissions, and cost were investigated.

4 Life-Cycle Optimization Method and Applications

4.1 LCO Method

The LCO model is constructed using a dynamic programming method. Dynamic programming is a mathematical tool used to find an optimal sequential decision (or optimal path) that best satisfies a decision maker's objective such as economic cost. The optimal path of decisions minimizes the cumulative life-cycle inventories (LCIs) (or costs) incurred from producing (or purchasing), using, and disposing of a series of product model years.

Figure 2 is a schematic example of the LCO model applied to product replacement. The *y*-axis depicts the cumulative environmental burden of a criterion (e.g., CO, NMHC, NO_x, CO_2, or energy consumption), while the *x*-axis represents time. The initial product is assumed to be produced at time 0, and a new model product with a different environmental profile is introduced at time T_a and T_b. Decisions to keep or replace products are made at the points marked by black dots. Materials production and manufacturing environmental burdens are shown as a step function at the time a product is produced. The slope of each line segment represents an energy efficiency or emission factor of a product depending on the criterion to be minimized. The slopes tend to increase with time, indicating possible deterioration in energy efficiency or other burdens. Assume that, at time 0, a decision maker tries to minimize the environmental burden of a criterion within the time horizon *N* based on information the decision maker has regarding the

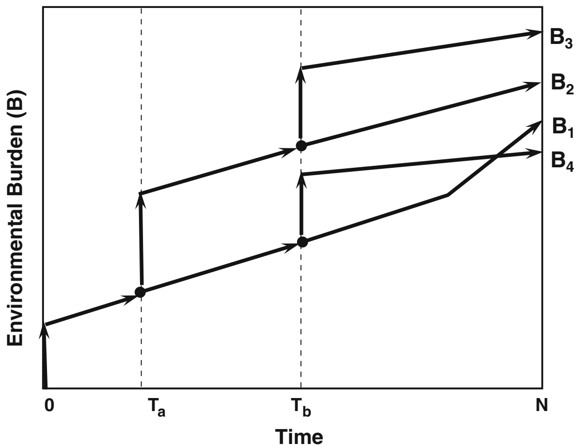

Fig. 2 Schematic example of the life-cycle optimization (LCO) model based on four policies. B_1–B_4 represent the final environmental burdens for the four policies

environmental performance of future product models. The decision maker seeks a solution of the form "Buy a new product at the start of year 0 and keep it for R years and retire it; then buy a new product at the start of year R and keep it for $\hat{a}$ years and retire it, etc." As an example, consider four policies depending on the decisions at T_a and T_b. It is assumed that retiring a product and buying a new product occurs simultaneously.

(1) If the product owner keeps the initial product throughout the time horizon N, the cumulative environmental burden (B) will result in B_1. The slope change between T_b and N represents product deterioration expected for older products.
(2) If the product owner replaces the initial product with a new product at time T_a and keeps the new product until N, the cumulative environmental burden (B) will result in B_2.
(3) If the product owner replaces the initial product with a new product at time T_a and replaces this second product again at T_b, the cumulative environmental burden (B) will result in B_3.
(4) If the product owner replaces the initial product at time T_b with a new product and keeps the new product until N, the cumulative environmental burden (B) will result in B_4, which is the minimum possible outcome.

With this hypothetical example, policy (4) is the optimal policy, and the optimal product lifetimes are T_b and $N - T_b$. However, in a real-world problem with a longer time horizon, the number of possible policy choices is often enormous. If a decision maker seeks an optimal replacement policy during a time horizon N with a new product at the beginning of year 0, and the product replacement decisions are made at the beginning of every year from year 1, the number of possible outcomes is 2^{N-1}. In addition, the environmental profiles of N different model years need to be considered based on product age. The LCO model provides an efficient algorithm to find an optimal policy, and the dynamic LCIs determine the environmental profiles of each product's model year and age.

In a typical dynamic programming model, a set of system characteristics is defined in the state of the system for each time epoch. Decisions are made at each time epoch throughout the time horizon of optimization. A state is defined by a vector (i, j) that represents model year i and age j of a product. The dynamic LCIs and costs are characterized for each state of the system. The LCO model to find optimal refrigerator lifetimes for environmental criteria is constructed using the following notations and equations:

n	First year
N	Last year
M	Maximum physical life
$B_M(i)$	Environmental burden (hereafter called burden) from the materials production of model year i
$B_A(i)$	Burden of the manufacturing of model year i
$B_U(i, j)$	Burden of the use phase during year j of model year i

$B_E(i, j)$ Burden of the end-of-life stage of model year i retired at the end of year j
$u(i, j)$ Cumulative burden of purchasing (producing) a new product at the start of year i and keeping it for j years. For any model year i, $u(i, 0) = 0$
$f(i)$ Minimum possible burden accumulated from the start of year i through the end of year N given that a purchase is made at the start of year i
x_i Number of years owning product of model year i

$$u(i,j) = \begin{cases} B_M(i) + B_A(i) + B_E(i, i+j-1) + \sum_{k=1}^{j} B_U(i,j) & \text{if } j > 0 \\ 0 & \text{if } j = 0 \end{cases} \quad (1)$$

$$f(i) = \begin{cases} \min\limits_{x_i \in \{1,2,\ldots,M\}} \{u(i, x_i) + f(i + x_i)\} & \forall\, i = n, \ldots, N \\ 0 & \forall\, i > N \end{cases} \quad (2)$$

For each criterion, this model seeks to minimize the environmental burdens from the life-cycle of model years n to N by deciding x_i, the number of years before purchasing a new product. A computer program to find the optimal path of sequential replacement decisions was coded using C language. A similar LCO model was also constructed for the cost criterion considering the life-cycle costs from purchasing, using, and disposing of a product.

4.2 LCO Application to Automobiles and Refrigerators

The application of the LCO method requires the construction of an LCO model based on life-cycle profiles for environmental burdens (e.g., energy), impacts (e.g., global warming impacts), and costs as shown in Fig. 3. The life-cycle profiles for each model year option are inputs into the LCO model and the simulation results generate the optimal replacement schedules. The life-cycle energy profiles for the

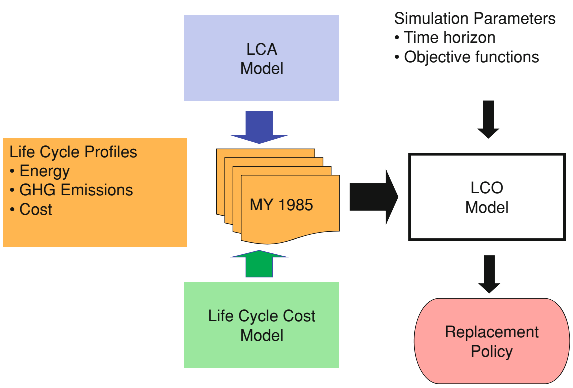

Fig. 3 Life-cycle optimization model structure and input

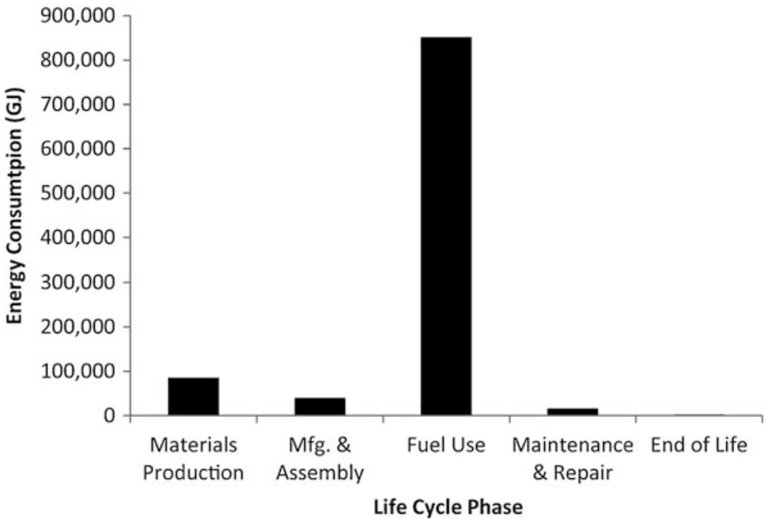

Fig. 4 Life-cycle energy consumption for a 1995 generic vehicle based on 120,000 miles of driving

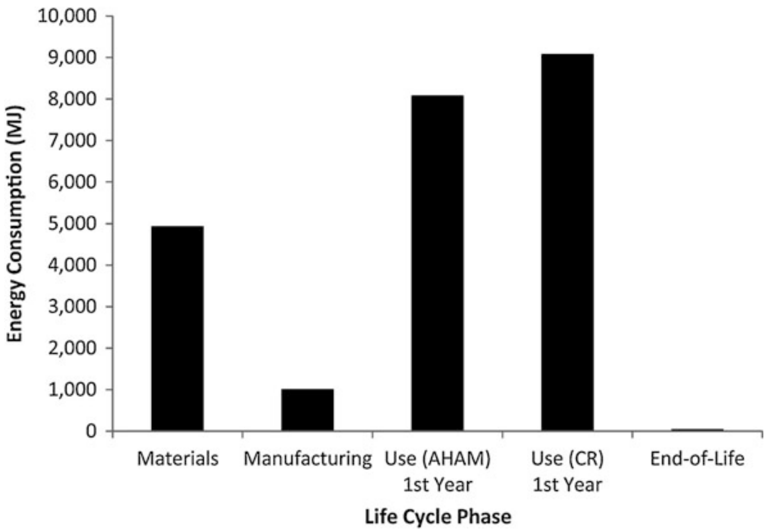

Fig. 5 Life-cycle energy consumption based on 1-year usage of mid-sized 1997 refrigerator model (*CR* Consumer Reports, *AHAM* Association of Home Appliance Manufacturers survey)

mid-sized automobile and household refrigerator are shown in Figs. 4 and 5, respectively.

The production and use phase burdens for each model year are determined from historical records and projections are made for future improvements. For example, the use phase energy consumption trends and simulation forecasts used for the

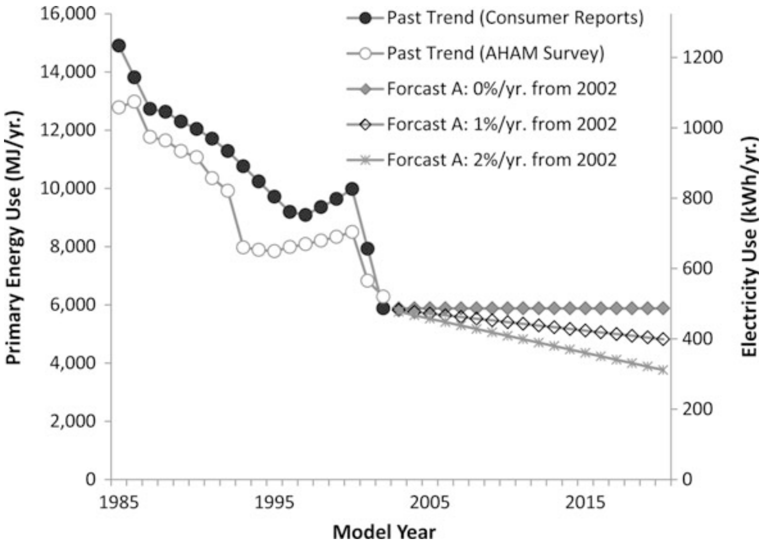

Fig. 6 Past trends and future forecast scenarios of energy use during the first year of a new refrigerator model. *Forecasts A*, *B*, and *C* assume that the energy consumption for a new model refrigerator would decrease 0 %/year, 1 %/year, and 2 %/year of 2002 model, respectively (AHAM 2003; Consumers Union 2002)

refrigerator LCO study are shown in Fig. 6. A maximum lifetime of 20 years for all refrigerator models was used as a modeling constraint.

For the fuel economies of average new cars between 2000 and 2020, the reference case scenario of US DOE Energy Information Administration Annual Energy Outlook 2001 was selected. According to this source, fuel economies will increase from 27.0 to 32.5 miles per gallon between 1985 and 2020 for an average new car. A maximum physical lifetime of 20 years for all mid-sized passenger car models was assumed as a modeling constraint. A detailed description of model parameters is provided in Kim et al. (2003) for the LCO automobile study and Kim et al. (2006) for the LCO refrigerator study.

5 Results and Analysis

5.1 Automobiles

The LCO model was applied to US mid-sized cars to evaluate the optimal lifetime and recommend future policies. The simulations were conducted to minimize energy consumption, CO_2, CO, NO_x, NMHC, and cost. The model years for the simulations are set between 1985 and 2020 and the maximum physical life of a vehicle (*M*) is assumed 20 years.

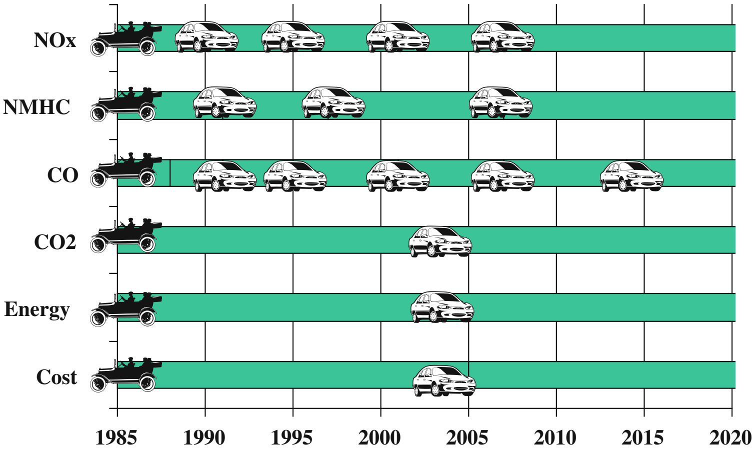

Fig. 7 Optimal vehicle replacement lifetimes for minimizing life-cycle NOx, NMHC, CO, CO_2 and cost objectives over the 1985–2020 time horizon

Figure 7 presents the simulation results for each objective. The timing of each vehicle replacement is indicated by a vehicle icon. The optimal set of lifetimes for the CO_2 objective, for example, can be interpreted as "keep the model year 1985 car for 18 years and retire it at the end of 2002, then buy a model year 2003 and keep it for another 18 years until 2020 in order to minimize CO_2 emission when driving a vehicle 12,000 miles per year." The energy and cost optimum policy are also similar (18, 18 replacements), The reason for the long optimal service life is that the savings from improvements in new model fuel economy are very small compared to energy, cost, and CO_2 emissions from production of the new model vehicles. The identical results for the energy and CO_2 objectives can be attributed to the fossil fuel combustion, which accounts for the majority of both energy consumption and CO_2 emission during a vehicle life.

In contrast to the energy, CO_2, and cost objectives, the replacement policy for the regulated pollutants occurs at much more frequent intervals due to dramatic reductions in vehicle tailpipe emissions over time. These rates of improvement are the dominant factor in influencing replacement policies: the NO_x optimum policy (5, 5, 6, 6, 14), the CO optimum policy (3, 3, 4, 6, 6, 7, 7), and the NMHC optimum policy (6, 6, 10, 14).

The optimal vehicle life generally decreases with increasing annual VMT. This result can be explained by the growing dominance of vehicle use phase emissions and energy consumption as well as a higher deterioration rate from increasing annual VMT. In other words, as the VMT increases, driving a new, lower-emitting, and efficient vehicle becomes more important while the additional emissions from retiring an old vehicle and producing the new vehicle become relatively insignificant.

5.2 Refrigerators

The optimal lifetime of refrigerator model years between 1985 and 2020 is determined for the objectives of energy, cost, and global warming impact (GWI) on the basis of the dynamic LCI datasets assuming a 20-year maximum physical lifetime. Figure 8 shows the optimal lifetimes as well as the cumulative LCIs and costs from the model runs assuming that a consumer purchases a new refrigerator at the beginning of 1985. The optimal set of lifetimes for the energy optimization policy based on the data from Consumer Reports can read, for example, "keep the model year 1985 refrigerator for 2 years and replace it with a model year 1987, keep the model year 1987 for 5 years and replace it with a model year 1992,…, and keep the model year 2014 refrigerator for 6 years, in order to minimize the cumulative energy usage over the time horizon between 1985 and 2020." As can be seen, optimal refrigerator lifetimes for energy and GWI objectives are significantly shorter than those for cost objective and the real-world average. The similar results for the energy and GWI objectives may be associated with the fact that the CO_2 emissions associated with electricity generation and refrigerator production are the most dominant global warming gases. However, from a consumer's perspective, such frequent replacements would be impractical considering the 36–50 % additional cost to the cost optimal policy (lifetime of 18 years). On the other hand, the cost optimal policies incur 22–24 % additional energy consumption compared to the energy optimal policies.

The efficiency improvement forecasts for future model years can affect the optimal lifetimes of future models for the energy objective. The benefits of replacing old models with new models grew in parallel with improving efficiencies

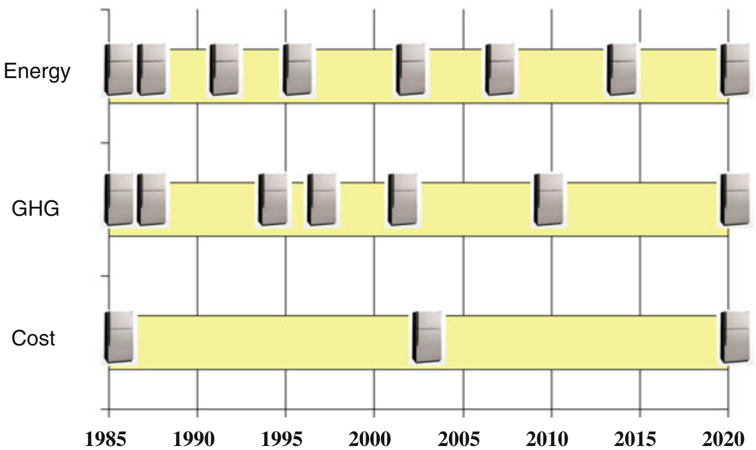

Fig. 8 Optimal refrigerator replacement lifetimes for minimizing life-cycle energy, global warming impact (GSI) based on greenhouse gas emissions (GHG), and cost objectives over the 1985–2020 time horizon

over model years. However, optimal lifetimes for the cost objective were unresponsive to the efficiency improvement scenarios probably because the efficiency changes have a relatively small impact on the life-cycle costs. Deterioration was also an important factor that influenced optimal lifetimes. The benefits of frequent replacement of refrigerators also grew with rapid deterioration of efficiencies as refrigerators aged.

Optimal lifetimes are affected by efficiency scenarios and assumptions, along with life-cycle environmental and cost profiles. Nonetheless, the overall trends—short optimal lifetimes for energy and GWI objectives and long optimal lifetimes for the cost objective.

The LCO simulation was also run from the perspective of a current owner in 2004. The results indicated that replacing an existing mid-1990s or previous model (with over 1,000 kWh annual energy use) at the beginning of 2004 is beneficial from both cost and energy perspectives. Strictly from an energy perspective, the customer would replace any refrigerators older than 2001 but this is clearly not cost effective.

6 Conclusions

The LCO model can provide useful information to consumers, designers, manufactures, and policy makers for improving the sustainability performance of product systems for meeting societal needs. This model indicates the optimal replacement schedules for products with respect to specific environmental objectives. The LCO model described in this chapter was applied to two different product systems yielding very different optimal replacement schedules.

The optimal replacement schedule results for both product systems indicate that the replacement frequency depends on several key factors including: the specific objectives, the rate of future technology improvements, the impact distribution between production (fixed) and use (marginal) activities, consumer use patterns, and deterioration in product performance over time (e.g., vehicle emissions).

Although the use phase is the most dominant source of environmental burdens for both automobiles and refrigerators, the characteristics of energy efficiency improvement and deterioration are quite different. Until recently, the fuel economy standards for automobiles had remained nearly unchanged since the mid-1980s and fuel economy deterioration with vehicle age is known to be negligible. In the case of refrigerators, on the other hand, major efficiency improvements were achieved in the last decade, primarily due to the series of federal energy efficiency standards for appliances enacted in 1990, 1993, and 2001. Also, deterioration is likely to be a significant factor for increasing electricity consumption. Therefore, the optimal lifetimes for the energy objective were considerably shorter in the case of refrigerators (2–7 years for the baseline scenario) than in the case of automobiles (18 years) if optimized over model years between 1985 and 2020.

The design life and durability of a product would ideally be related to the rate of efficiency improvement. Products based on rapidly changing technology may not be proper candidates for enhanced design durability. If a simple product will soon be obsolete, making it more durable could be counterproductive. In complicated products subject to rapid change, adaptability is usually a better strategy. For example, modular construction allows easy upgrading of fast changing components without replacing the entire product. In such cases, useful life is expected to be short for certain components, so they should also not be designed for extreme durability.

In addition to temporal considerations, product replacement policy can also be influenced by geographical location. A recent study of household central air conditioners indicates how optimal replacement schedules are influenced spatially by climate zones and how regional standards can be effective in achieving greater environmental and economic benefits than national standards (De Kleine et al. 2010a, b).

Life-cycle optimization provides a decision-making tool for managing not only consumer products, but large-scale systems such as buildings and infrastructure. For example, the LCO model has also been applied to infrastructure systems that require large capital investments with maintenance costs and have long service lives. Road pavement poses significant modeling challenges given the interactions between pavement and vehicle systems. Models are required to simulate congestion related to road construction events, road deterioration behavior, road roughness effects on fuel economy, and vehicle technology improvements. Here optimization is used to determine asset management decisions including budget allocation decisions, pavement material selection, and the timing and frequency of rehabilitation events. The LCO method was recently applied to alternative road pavement overlay systems (Zhang 2009; Zhang et al. 2010a, b).

Developing LCO models can be valuable in informing the key decision makers responsible for these transformations including consumers, manufacturers, the service industry, and government agencies that set standards and create incentives. There is tremendous opportunity to accelerate the replacement or renovation of the existing stock of products such as automobiles and consumer appliances to enhance environmental sustainability performance. The case studies conducted by the Center for Sustainable Systems have shown how LCO can become an important sustainability tool for guiding product design and policy decisions in the future.

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Second Thoughts on Preferred End-of-Life Treatment Strategies for Consumer Products

Joost R. Duflou, Joris Van Ostaeyen and Wim Dewulf

Abstract Traditionally, eco-design has been steered by an implicit hierarchy of preferences with respect to the end-of-life options for products of which the total life cycle impact is to be minimised. In this context, life time extension is typically preferred over disassembly for reuse of components, which in its turn is preferred over material recycling. However, this priority hierarchy is often too simplistic to accept it as a general applicable guideline: both ecological and economic considerations can make life time extension and/or the reuse of components non-favourable strategies in cases where product performance and resource efficiency may evolve rapidly as a result of continuous innovation. Furthermore, where ecological indicators might confirm the suitability of a life time extension strategy at component level, economic constraints often make such scenarios infeasible. De facto today few disassembly activities prove to be economically viable. However, the emergence of new technologies and business models could indicate a reversal of the trend to abandon the higher priority end-of-life treatment methods for manufactured goods. Based on extensive, case study driven research, successful business models were revealed that improve the economic viability of systematic product reuse, refurbishment or disassembly in function of component reuse. Where material recycling proves to be the only realistic scenario, newly emerging self-disassembly techniques could help to improve the feasibility of pure material fraction separation before shredding is applied.

Keywords End-of-life treatment · Eco-design · Life time extension · Reuse · Self-disassembly · Product-service systems

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1 Introduction: Traditional End-of-Life Priority Hierarchy

Reaching a convenient level of comfort [higher levels of the Maslow pyramid (Maslow 1943)] unavoidably requires adjustments to our natural environment. These changes are typically implemented through the application of a range of products and systems, the manufacture and use of which results in environmental impact. Impact avoidance by eliminating the need for such products is in many cases technically not feasible without reducing the comfort levels offered. Traditionally the approach advocated for impact minimisation has therefore been to aim at the conservation of the integrity of products in their end-of-life (EOL) stages, thus spreading the impact of production and EOL treatment over a maximised functional life span. In times when landfill problems were becoming more and more visible, the target of waste avoidance indeed seemed an obvious priority. To maximise the functional life time of products and systems seems a logical solution to support or further this approach. When wear and tear or functional requirement shifts finally result in the decision to discard products, the same logic can be repeated at component level. In a dogmatic vision reuse of subsystems is typically only considered a suitable EOL destination for product components when the product integrity cannot be preserved. Where final discarding of products and components seems unavoidable, closed loop recycling comes into the picture. Here the major concern is to assure sufficient material purity in order to allow reuse of materials without significant quality deterioration. The recent Cradle to Cradle hype (McDonough and Braungart 2002) is merely an extension of this strategy to biosphere recycling of renewable material categories. The preference list can be extended up to the ultimate lowest priority level of discarding in landfills. Such priority ranking approaches have been formalised in a series of publications and have also affected governmental policies in a number of countries. In the Netherlands, for example, the so-called Ladder of Lansink (Fig. 1) was introduced as a policy instrument in a parliamentary debate in 1980 (Lansink 1980 and OECD 1982).

The maturity that life cycle assessment quantification techniques have reached today allows verification of the correctness of the assumed impact minimisation strategies underlying such EOL treatment priority hierarchies. In Sect. 2 the analysis results for a number of specific doubt cases are reported. Besides

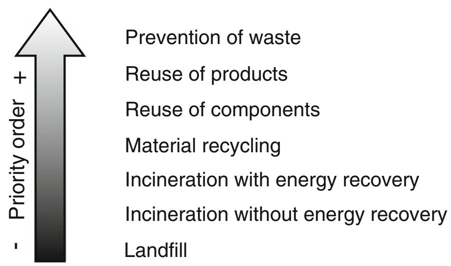

Fig. 1 Lansink's ladder: ecological hierarchy of end-of-life options (Lansink 1980)