A LIFE CYCLE ENVIRONMENTAL AND ECONOMIC COMPARISON OF CLOTHES WASHING PRODUCT-SERVICE SYSTEMS

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ABSTRACT

Manufacturers are increasingly designing and creating integrated product-service systems (PSS) to improve customer satisfaction and take advantage of opportunities for product life cycle management, including improved upstream information flow to product design and manufacturing. Two PSS for clothes washing are compared in terms of life cycle economic and environmental impacts. The two PSS investigated are a laundry service and home-based clothes washing. It is shown that home-based washing has 1.5 times the environmental impact of a laundry service, due to increased materials use, while costs are reduced by about 85% due to elimination of labor and overhead. The comparison suggests that a more service-oriented PSS has less environmental impact and higher costs. Therefore, improvement efforts should be focused on reducing the labor content for high service PSS, and reducing the amount of material within product-oriented PSS. It was also found that service-oriented PSS can result in higher transportation impacts.

INTRODUCTION

Manufacturers use large amounts of materials and energy to satisfy consumer needs. To address increasing pressures to reduce energy use, greenhouse gas (GHG) emissions, and waste, companies are embracing sustainability principles. Several recent papers have begun to address environmental issues in manufacturing (Tumkor et al. 2004; Román and Bras 2006; Dornfeld and Wright 2007). One strategy that has begun to receive increasing attention is servicizing (White et al., 1999). Servicizing, which is the transition from selling a physical product to selling the function provided by the product, e.g., leasing, offers intriguing opportunities for sustainable manufacturing. Specifically, servicizing allows the manufacturer to retain more control and have more knowledge of a product over its life, which can aid in reducing life cycle environmental impacts.

While service-focused businesses represent a strategy to pursue sustainability, service has long been recognized as a key aspect of successful businesses. This recognition has evolved into an area that has begun to receive increasing attention from corporations: product-service systems (PSS). Since service has long been part of the corporate framework, one might ask, "why the growing interest in PSS?"

Historically, products have been designed and manufactured, and services designed and provided as separate functions. The interest in product-service systems (PSS) fundamentally asks manufacturers to revisit the manner in which the needs of a customer are met (Lindahl et al. 2007). PSS can be defined as the integration of products and services to fulfill a need. Product-service systems are comprised of the "provider" (e.g., manufacturer, supplier, and service providers) and customer, and have several distinguishing characteristics (Aurich et al., 2007):

- Customers expect certain functionalities of the products and services that are provided,
- The states of the product, user, and provider change continuously over the life cycle, and
- The service network allows information to flow between the provider and customer.

Conventionally, product manufacturers have focused on product design and manufacturing, but a life cycle perspective is shifting focus toward service, end-of-use (EOU), and end-of-life (EOL) options. The distinction is made between EOU and EOL products, since products may undergo multiple use cycles. From the customer perspective, life cycle concerns include product procurement, use, and end-of-use options. To compete in the changing industrial landscape, manufacturers must optimize product designs with a broader perspective (i.e., material extraction/processing, manufacturing, use, and end-of-life) in concert with service providers and consumers.

A paradigm shift toward product-service systems requires a fundamental re-examination of the design of the product and service, perhaps to improve the ease of disassembly and promote end-of-use (EOU) value recovery. An increase in recovery efficiency can result in purities nearly equal to virgin materials, and raise material value (Nakamura and Kondo 2006). Through periodic inspection and maintenance, valuable components can be recovered through the service network (Kumar et al. 2007). Life cycle management within a PSS can thus capture value remaining in an EOU product.

Continued utilization of the function and value of components is possible by product takeback at collection points and through distributors, recyclers, or manufacturers. Some EOU parts or assemblies may be worn and require recycling, while others can be reused or remanufactured. With information collected on the condition of end-of-use products and modes of failure, components can be redesigned for improved longevity or ease of repair.

The success of product and material recovery strategies is dependent upon the choices made during the design and manufacture of the product and the effectiveness of service delivered over its life. By providing the use of a product to a consumer, rather than the product itself, PSS inherently can lead to the reduction of materials use and facilitate energy efficiency, reuse, and recycling efforts through responsive product design. In addition to environmental sustainability goals, the need for skilled service providers can reduce unemployment, and support the goals of economic and societal sustainability.

To support these sustainability goals, manufacturers must work to develop specialized products suitable for use within PSS, rather than a flood of mass-produced products that perform the same function. As an example, a common everyday function, clothes washing, is examined in terms of its economic and environmental aspects for two PSS. The analysis methodology and assumptions are outlined for a laundry service using on premise laundry (OPL) washer-extractors and homes using standard residential washing machines.

BACKGROUND

Millions of people in modern society are provided with numerous laundry-related products and services. These include home washing machines, coin laundromats, and laundry services (e.g., drycleaners and full-service laundries). Laundry products require a large amount of energy and materials to manufacture and use. Some detergents may ultimately lead to environmental harm (e.g., perchloroethylene).

Perhaps the most prevalent clothes washing method in the developed world uses a residential washing machine. Factors influencing whether a consumer chooses a laundry service or purchases a home washer include income, family size, and geographic location (Purchase et al. 1982). Another segment of the clothes washing industry is the full-service laundry, which picks up soiled laundry from businesses, campuses, and homes, launders it, and returns it for a fee. Pick-up laundries serve many college campuses and metropolitan areas. Low et al. (2000) studied laundries in the United Kingdom that provide hygienically laundered diapers, or *nappies*, in exchange for soiled ones. Parents have the convenience of clean diapers without purchasing disposables or the need to launder their own. The study found that environmental impacts were also reduced.

For the case of home-based washing (Fig. 1a), the manufacturer ships the clothes washer to a retailer and the consumer subsequently purchases the product. The consumer uses the washer, which may later be transferred to another household. Service is provided by the retailer or a repair business over the life of the machine, and it is ultimately brought to a recycler for scrap metal recovery.

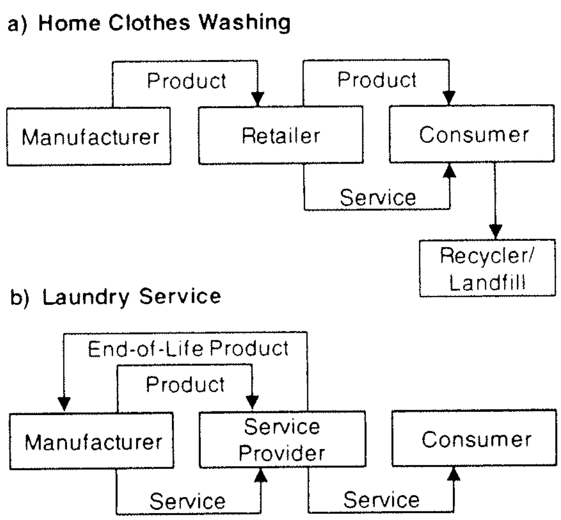

FIGURE 1. TWO PRODUCT-SERVICE SYSTEMS.

In the case of a laundry service (Fig. 1b), manufacturers provide washer-extractors and product management to service partners. In turn, laundry services deliver washed clothes to consumers. Washers are ultimately taken back by the manufacturer for value recovery. The comparison of the two PSS is described below.

ANALYSIS METHODOLOGY

In the study undertaken to compare the two product-service systems in terms of life cycle costs and environmental impacts, several assumptions were made. The functional unit used was the annual volume of clothes needing laundering by 240 households. It was assumed that the laundry service has 10 washer-extractors capable of serving 240 households, weekly. Data for the laundry service and home clothes washing are provided in Table 1.

TABLE 1. DATA FOR A LAUNDRY SERVICE AND HOME CLOTHES WASHING.

	Laundry Service	Home
Clothes washed per machine (loads/yr.)	3744	392[a]
Number of washing machines	10	240
Washing machine capacity (m^3)	0.21	0.08[a]
Weight of washing machine (kg)	475.82[b]	58.83[c]
Washing machine life (yr.)	5	11[a]

[a]EnergyStar, 2007; [b]Continental, 2007; [c]Bole, 2006

Of course, there is a high variability of washing habits among households and many different washing machine designs. In terms of use-stage impacts, this study considers the washing habits of an average U.S. household. Manufacturing impacts are based on the average composition of a washing machine as described below.

The material composition of a home washer was modeled using an average 2005 washing machine and, while the material composition was not readily available for washer-extractors, the material fractions were assumed to be the same as a 2005 horizontal-axis washer as shown in Table 2 (Bole 2006).

TABLE 2. COMPOSITION OF A WASHER-EXTRACTOR AND HOME WASHER (BOLE 2006).

Material Composition (values in % mass)	Laundry Service	Home
Steel	50.38	73.01
Iron (gray cast)	0.05	0.69
Aluminum	3.22	4.55
Copper	1.28	2.00
Other Metal	0.15	0.00
Rubber	1.74	1.85
Fiber & Paper	3.88	0.00
Polypropylene	15.59	15.42
ABS	1.33	0.08
PVC	0.97	0.93
Other Plastics	2.55	1.39
Glass	1.94	0.00
Other	16.91	0.08

To estimate the typical material composition of laundry service washer-extractors, data on more than 20 on-premise laundry (OPL) machines were gathered. Machines with load capacities of 15-30 kg were found to have masses of 245-815 kg, with an average mass of 473 kg. A washer-extractor with a 476 kg mass and load capacity of 18 kg was selected; it was the only machine with published water and energy use data (Continental 2007). The washer was assumed to be capable of processing laundry for one household in three loads, weekly.

To assess impacts of washing machine use, energy and water were considered. The U.S. DOE and U.S. EPA certify washing machines with EnergyStar ratings. Modified energy factors (MEFs), established by product testing, aggregate the energy consumed due to washer operation, water heating, and clothes drying. Standard-sized washer operational energy, water heating energy, and water use are available (EnergyStar 2007). With this data, use scenarios could be established (Table 3).

TABLE 3. ENERGY AND WATER USE FOR A WASHER-EXTRACTOR AND A HOME WASHER.

	Laundry Service	Home
Electricity (kWh/yr.) [a]	486.7	213.6
Natural Gas (kWh/yr.) [a]	2304.3	
Water (L) [a, b]	435674.3	34984.6

[a]EnergyStar, 2007; [b]Continental, 2007

An environmental impact analysis for the manufacture, use, and recycling of the two washers was completed using a life cycle analysis (LCA) tool (SimaPro 7). The breakdown of electricity generation used is based on U.S. electrical energy sources (Table 4).

TABLE 4. ELECTRICAL ENERGY SOURCES IN THE UNITED STATES (EIA, 2006).

Energy Source	Power Generation (%)
Coal	49.7
Nuclear	19.3
Natural gas	18.7
Hydroelectric	6.5
Petroleum	3.0
Other renewables	2.3

Process profiles available in the LCA software package were used for electrical energy sources and heating with a natural gas boiler, as well as for tap water. Transportation data and one-time costs were distributed evenly over the life of the products. To capture the economic and environmental effects of the key service differences of the two systems, assumptions were made for product delivery, laundry pick-up and delivery, and product takeback or disposal, as shown in Table 5.

TABLE 5. TRANSPORTATION INFORMATION.

Distance from manufacturer (km)	800.00
Hauling truck fuel economy (L/100 km) [a]	36.96
Hauling truck capacity (tonnes) [b]	17.50
Distance from retailer to consumer (km)	16.00
Delivery truck fuel economy (L/100 km) [a]	22.53
Delivery truck capacity (machines)	4.00
Diesel price ($/L, Sep. 06-Aug. 07) [c]	0.71
Annual delivery distance (1000 km)	39.93
Delivery van fuel economy (L/100 km) [d]	18.20
Distance to scrap yard (km)	8.00
Light truck fuel economy (L/100 km) [e]	13.75
Light truck capacity (machines)	1.00
Gasoline price ($/L, Sep. 06-Aug. 07) [c]	0.69

[a]Davis and Diegel, 2007; [b]FHWA, 2001; [c]EIA, 2007; [d]EPA, 2007; [e]EIA, 2005

To assess the transportation impacts for both scenarios, profiles were selected that were most similar to the transportation mode used. Delivery and takeback of washers from the retailer and laundry service is completed with the use of a 40 tonne hauling truck. Delivery of washing machines to homes relies on the profile for a 16 tonne delivery truck. Pick up and delivery of clothing and transfer of the end-of-life residential washer to the recycler use the profile for a van, which has similar fuel economy to a light truck.

As noted previously, product-service systems provide an incentive for manufacturers to design products that can be easily disassembled, since the manufacturer maintains responsibility over the product life cycle. To simulate this opportunity, it is assumed that most of the metals and plastics in the washer-extractor are ultimately recycled. Conversely, only the steel, iron, and aluminum are assumed to be recycled from the residential washer. Material profiles to account for washer material use included those for steel sheet, cast iron, aluminum, glass, paper, polypropylene, and PVC pipe. Recycling profiles used were for steel and iron, aluminum, glass, paper, polypropylene, and PVC

Upon completion of the life cycle inventory, an impact analysis of both alternatives, i.e., washer-extractor and home washer was conducted.

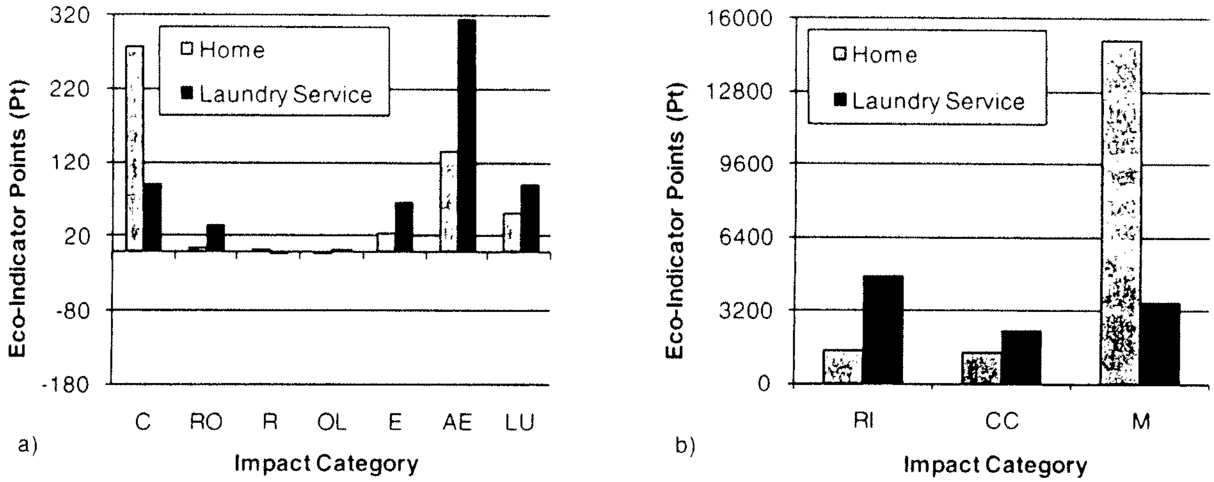

FIGURE 2. LIFE CYCLE ENVIRONMENTAL IMPACTS OF A HOME AND LAUNDRY SERVICE.

ENVIRONMENTAL COMPARISON

In the LCA software utilized for this study, environmental impacts are estimated in terms of carcinogens (C), respiratory organics (RO), respiratory inorganics (RI), climate change (CC), radiation (R), ozone layer (OL), ecotoxicity (E), acidification/eutrophication (AE), land use (LU), and minerals (M). Eco-indicator points, a measure of environmental impact equivalent to 1/1000 of the yearly environmental load of a person living in Europe, are determined for each impact category (Eco-indicator, 2000).

For the two laundry PSS, two situations were assessed. First, a comparison of manufacturing and use stages was conducted (Fig. 2). Second, a comparison of manufacturing, use, and end-of-life, e.g., recycling, was completed (Fig. 3). It can be seen that the laundry service has higher impacts except for carcinogens, radiation, and minerals with no recycling. With recycling, impacts are lower in all categories, while relative impacts of both PSS remain the same. It is interesting to note that the home washing PSS with recycling results in a net environmental benefit in terms of carcinogens.

Because of the material requirements of many washing machines, the minerals (M) category dominates the impacts of home-based washing. In contrast, respiratory inorganics (RI) are the highest impact category for a laundry service, likely due to the operation of the delivery van. Overall, for 240 households, home-based clothes washing has about 1.5 times the impact of a laundry service. Recycling reduces the environmental impacts by 23% and 7% for the home and laundry service, respectively (Fig. 4).

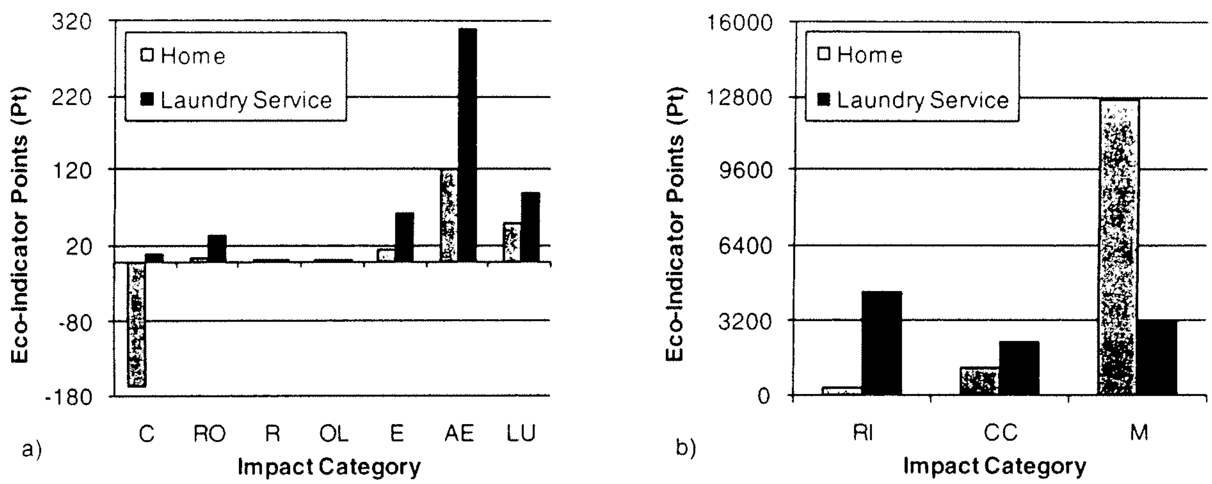

FIGURE 3. ENVIRONMENTAL IMPACTS OF A HOME AND LAUNDRY SERVICE INCLUDING RECYCLING.

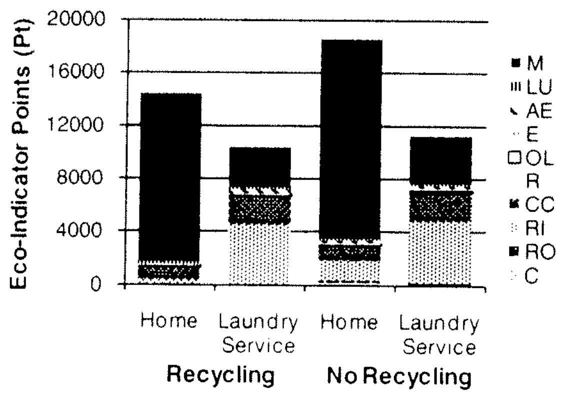

FIGURE 4. OVERALL ENVIRONMENTAL IMPACTS.

Since there is uncertainty associated with inventory data and data-to-impact mapping in life cycle analysis, the LCA software allows analyses to be performed from three perspectives, known as Egalitarian, Hierarchist, and Individualist archetypes. Each archetype places slightly different importance on types of environmental damage, i.e., Human Health, Ecosystem Quality, and Resources, to reduce uncertainty effects. For example, Egalitarian weights Ecosystem Quality as 50% of the total damage, while Hierarchist weights it as 40% and Individualist as 25% (Eco-indicator, 2000).

The levels of impact for each of the environmental damage group types (Human Health, Ecosystem Quality, and Resources) were compared. For each archetype, the relative environmental impacts were found to be similar. The life cycle damage results for the Individualist archetype are reported in Figure 5.

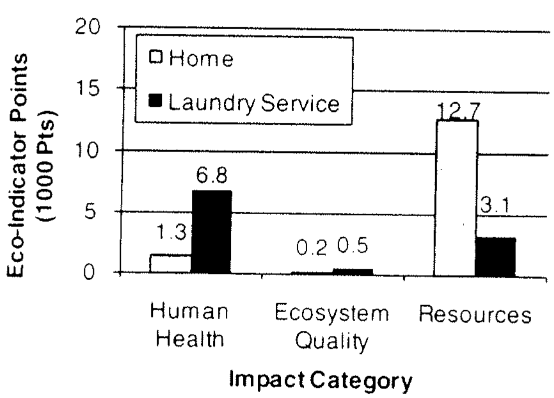

FIGURE 5. DAMAGE ASSESSMENT FOR BOTH PRODUCT SERVICE SYSTEMS WITH RECYCLING.

For home washing, Resources damage appears to have the highest importance, likely due to materials and water use over the life cycle. In terms of Human Health and Ecosystem Quality, the laundry service has higher relative damage; although damage to Ecosystem Quality is relatively small for both PSS. The higher damage to Human Health from the laundry service is likely due to vehicle use in picking up soiled laundry and delivering cleaned articles. An examination of the processes with the most significant effects on environmental impacts for each scenario found this to be the case.

Figure 6 shows that the operation of the delivery van has the highest process environmental impact for the laundry service. The production of copper has the highest impact over the home clothes washing life cycle. As would be expected, material production (copper, steel, and polypropylene) processes are among those with the highest impact for both PSS.

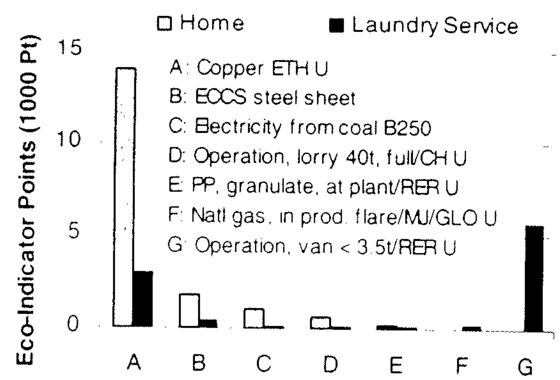

FIGURE 6. MAJOR PROCESSES INFLUENCING ENVIRONMENTAL IMPACTS.

The results of the environmental impact analysis illustrate the importance of considering the effects due to materials, energy, and water use, when comparing a home clothes washing and laundry service. Since both PSS involve transportation, impacts from vehicle use are not trivial and have been considered as well.

It is important to note that other factors that influence the environmental impacts of clothes washing were not considered in this study. These factors include the use of fabric softeners, detergents, and different water temperatures. Clothes dryers, which commonly use electricity or gas, also have a large influence on the environmental impacts of clothes washing. A laundry service may package clean clothes, which would not be done at home. Further, home plumbing and electrical systems serving home laundry rooms may be more material intensive than at a laundry service, where machines would be in close proximity.

The analysis described above illustrates how a paradigm shift in the manufacturing industry toward service-focused product-service systems can reduce life cycle environmental impacts.

ECONOMIC COMPARISON

In addition to life cycle environmental impacts, the annual household economic costs of using a laundry service and home-based clothes washing were analyzed using the information and assumptions presented above. Table 8 summarizes the results of this analysis.

TABLE 8. ESTIMATED ANNUAL COSTS FOR A LAUNDRY SERVICE AND HOME WASHING.

Costs in U.S. dollars	Laundry Service	Home
Product	2000.00	9272.73
Energy use	1284.19	5168.38
Water use	4786.11	9224.13
Shipping and deliveries	12130.79	
Labor	89856.00	
Overhead	44928.00	
Total costs	**154985.10**	**23771.11**
Weekly household cost	**12.42**	**1.90**

The economic analysis of the laundry service assumes washer-extractors are delivered from and returned to the original manufacturer using a diesel tractor trailer truck. It is also assumed that laundry pick-ups and deliveries take place once daily, six days per week using a gasoline-powered van. Water use is assumed to be 8.12 L/load at a cost of $1.099 per 1000 L. A standard home washer uses 8.59 L/load. Water is considered to be heated using a gas water heater ($0.0365/kWh for an industrial consumer) and require the same amount of energy as home washing (0.615 kWh/load). Electricity use ($0.09/kWh for an industrial consumer) was assumed to be 0.13 kWh/load, the same usage as a standard home washer (EnergyStar, 2007).

The home-based washing economic analysis assumes washing machines are an even mix of standard and EnergyStar-rated machines. An EnergyStar washer uses about 3.87 L/load, so water use is assumed to be 6.23 L/load. Water heating is considered to be achieved using an electric water heater requiring 0.425 kWh/load ($0.1008/kWh for a residential consumer). The electricity use is assumed to be 0.12 kWh/load (EnergyStar, 2007). In addition, washers are assumed to be delivered from the manufacturer to the retailer by a diesel tractor trailer truck and to the consumer by a diesel delivery truck. At the end of life, residential washing machines are transferred to a recycler with a pickup truck.

With respect to washing machine prices, electricity and water heating costs, and water costs, the laundry service is competitive with home-based washing. For a household, weekly costs are $1.90, while weekly costs are $1.60 at a laundry service. A service consumer, however, must also pay for the delivery of that service. Thus, it is assumed that the laundry employs three people 12 hours per day, six days per week, with an average wage of $12/hour. Indirect labor costs are assumed to equal the cost of wages, and overhead costs are half of the cost of labor (wages plus indirect costs). Thus, the laundry service requires a significantly higher investment than washing clothes at home ($12.42 vs. $1.90 weekly). Consumers must balance environmental impacts, costs, convenience, and social benefits (more time with family rather than doing laundry) when deciding which product-service system to use.

SUMMARY AND CONCLUSIONS

Two product-service systems (PSS), a laundry service and home-based clothes washing, were compared in terms of environmental and economic impacts. From an environmental perspective, home-based clothes washing has a greater impact, primarily due to material consumption. From an economic perspective, however, it is less expensive for the consumer. Some consumers may not be willing to pay an extra $10 per week for the convenience of a laundry service. Thus, manufacturers and service providers must continue to seek innovative ways to reduce costs and must pursue continuous improvement of design, manufacturing, use, and end-of-life, especially in the development of novel PSS.

Major areas of improvement include the reduction of environmental impacts of laundry pick-up and delivery and reduction of labor and overhead costs. Strategies must be developed to optimize delivery routes to reduce fuel consumption and to optimize operational activities. Products/systems must be created to improve material, energy, and labor efficiency, e.g., automation and reduced cycle times.

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