Challenges in Determining Electronics Equipment Take-Back Levels

Julie Ann Stuart, Ming Kaan Low, David J. Williams, *Member, IEEE,*
Laura J. Turbini, *Senior Member, IEEE,* Jane Chumley Ammons

***Abstract*—Industrial ecology requires life cycle planning and implementation. In order to replace product disposal with product take-back, reverse logistics networks and product take-back centers must be set up. Product take-back can be for reuse (repair, upgrade, and resale), recycling, or disposal. This paper focuses on the challenges in estimating product take-back levels. Current product take-back activities around the world are summarized. Product take-back cycles are defined and an improved product take-back estimation framework is proposed.**

***Index Terms*—Computers, electronics product take-back, end-of-life product returns, recycling.**

I. Introduction

A. Current Global Product Take-Back Activities

It is estimated that over 200 million computers will be either landfilled or recycled between 1985 and 2005; this end-of-life (EOL) activity is set against a proportionally large worldwide production of 150 million television and computer monitors per year [1]. Driven by the limitations of landfill space as well as the social and political climate to promote sustainability, take-back activities and legislation are increasing in various countries.

Disposal of electronic products in landfills is discouraged due to the presence of leachable lead, an element which is recognized by both the United States Environmental Protection Agency and the Basel Convention ("amber" classification) as a hazardous waste [2]. Particularly affected are printed circuit boards with tin/lead solders and cathode ray tubes (CRT's). In addition, electronic products also contain precious metals and plastics as well as ceramic and glass materials that may be reused if proper materials separation and recycling is available. The preferred ecological route to materials reuse is embodied within the concept of product reuse through repair, upgrade, and resale.

Manuscript received December 18, 1997; revised June 19, 1998. This work was supported by a National Science Foundation Graduate Research Fellowship, Institute of Industrial Engineers Gilbreth Memorial Fellowship, Georgia Tech Foundation Presidential Fellowship, British Telecom, AT&T (now Lucent Technologies), Motorola, NEC, and Loughborough University.

J. A. Stuart is with the Department of Industrial, Welding, and Systems Engineering, The Ohio State University, Columbus, OH 43210-1271 USA.

M. K. Low and D. J. Williams are with the Department of Manufacturing Engineering, Loughborough University, Loughborough, Leics, LE11 3TU, U.K.

L. J. Turbini and J. C. Ammons are with the Georgia Institute of Technology, Atlanta, GA 30332 USA.

Publisher Item Identifier S 1083-4400(98)07315-X.

Legislation for product take-back is increasing rapidly in Europe. The German Law IL 24 to Improve the "Closed-Loop Economy" and to Assure Environmentally Friendly Disposal of Wastes became effective October 6, 1996. In IL24, Section 22, product responsibility for developers, producers, and distributors is defined to include product design and implementation for minimum production waste as well as environmentally friendly recycling, reuse, and disposal at end of life [3]. In response to the EOL packaging take-back legislation in 1991 and the electronic product take-back proposed in 1995, the German reprocessing industry established 380 specialized recycling companies which include in excess of 45 facilities for recycling CRT's and 20 electronic scrap recycling facilities [4]. An additional 30 electronic scrap recycling plants are being planned or are under construction [5]. Legislation for electronics take-back has also been drafted in Denmark, Norway, Sweden, Switzerland, the Netherlands and the European Union (EU) affecting mainly household consumer electronics and information technology equipment [6].

Electronic take-back in the US has focused almost entirely on voluntary business initiatives with a few exceptions where government agencies have proposed or implemented recovery programs. Legislation pertaining to electronics take-back has been proposed but not mandated in Minnesota, California, North Carolina, Rhode Island, Texas and Wisconsin [7], [8].

Asian legislative activities for electronics take-back include Japan's Ministry of International Trade and Industry (MITI) draft amendment for producer responsibility for television and other appliances. Taiwan will be the second nation in the world, after Italy, to mandate take-back for computers, televisions, refrigerators, air conditioners and washing machines beginning in 1998 [8].

In addition to legislative mandates, voluntary corporate stewardship activities are increasing. For example, in the U.K. the Lothian and Edinburgh Environmental Partnership (LEEP), Electronic Equipment Manufacturers Recycling Group (EMERG), and the Industry Council for Electronic Equipment Recycling (ICER) have piloted projects that have collected over 100 million tons of electronic equipment in order to analyze the profitability of recovery [4], [9]. In the U.S., the National Safety Council formed the Electronics Recovery and Recycling (EPR2) Roundtable which is composed of representatives from original equipment manufacturers (OEM's), recycling companies, government, nonprofit organizations, and academia. This group is developing end-of-product life management strategies [10].

TABLE I
SUMMARY OF EOL DEFINITIONS

Reuse	**Resale**	The existing product is recovered and sold, with minimum alteration, to another customer requiring similar product function.
	Remanufacture	The product is recovered and restored to its original condition (both function and aesthetics).
	Upgrade	The existing product is given improved functionality and appearance.
Recycling		The product is disassembled to recover some components and base materials.
Disposal		Product and/or its elements go to landfill or incineration.

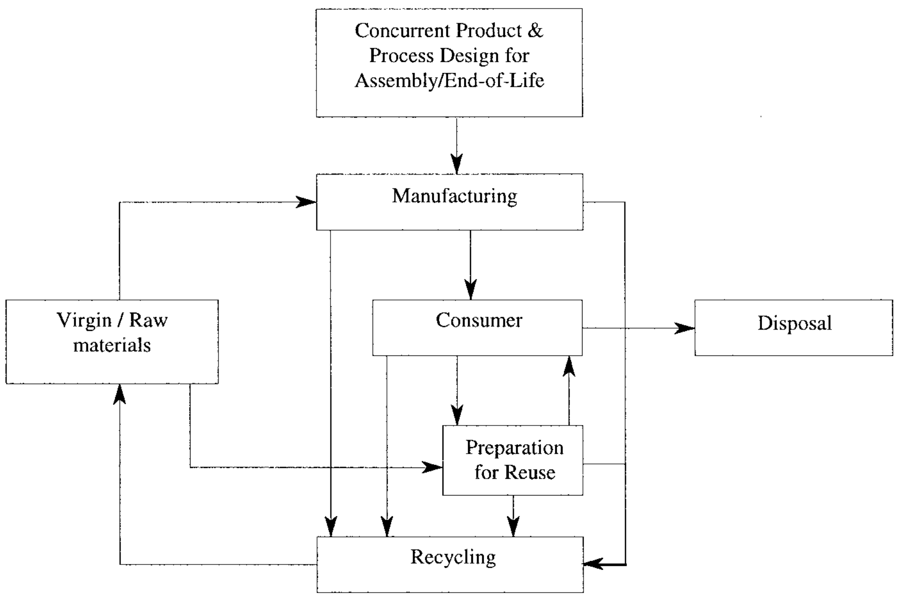

Fig. 1. Strategic life cycle product management perspective.

In this paper, we develop a framework for take-back rates for different EOL strategies. First, we define EOL strategies and explain how end-of-product life estimates assist with on going research in life cycle design and EOL management strategies. We define cycles of product take-back. Next we summarize historical product life estimation frameworks and propose a new framework for product take-back estimation.

B. The Product Life Cycle and Asset Management

The product stewardship obligations being proposed and in some countries enacted have been described in the previous section. These have led to the development of life-cycle design strategies for reuse, recycling and disposal that require estimates of the end-of-product-life returns in order to analyze the effects of different product designs on EOL strategies as shown in Fig. 1. Table I summarizes EOL definitions [11] generalized for electronics products.

There are several options for EOL activities including reuse, recycling, and disposal. Included in the reuse options are resale, remanufacturing, and upgrade. The purpose of reuse and recycling is to divert useful products and materials from landfills. However, the choice must be cost effective.

One approach to product life cycle and EOL planning involves defining take-back factors which link the manufacturing period in which the electronic product was produced to the period in which the product was taken back. To illustrate a take-back factor for repair, consider warranty returns. A manufacturer may record the date of manufacture for warranty returns in order to improve operating practices. For example, if a significant portion of products assembled in period 2 is returned in period 5, the manufacturer may try to determine the conditions in period 2 that led to the quality problem in period 5.

Similarly, take-back factors for reclamation may provide valuables insights for both manufacturers and EOL centers. To illustrate a take-back factor for reclamation, consider a take-back factor for nickel/cadmium (Ni/Cd) batteries. Linking the date of manufacture of Ni/Cd batteries to the date of take-back from consumers may also provide valuable insights for

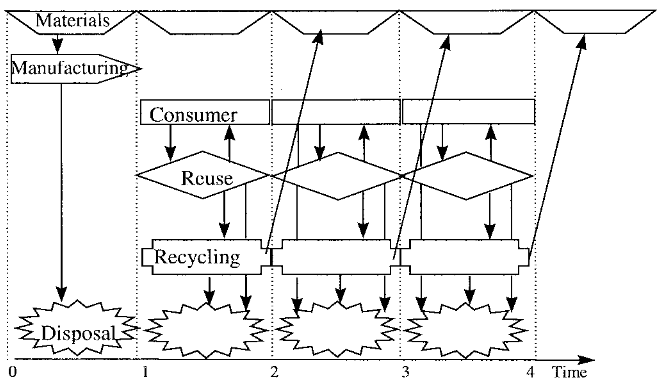

Fig. 2. Life cycle activities over time as a result of one manufacturing period.

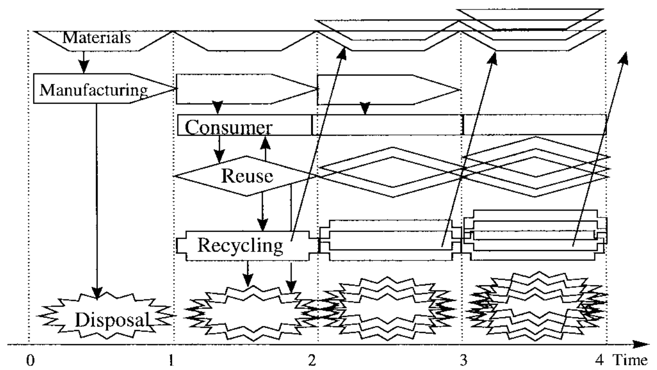

Fig. 3. Life cycle activities over time as a result of multiple manufacturing periods.

designers, manufacturers, and authorized battery reclaimers. The time-dependent relationships between materials selection and manufacturing operations, consumer use and EOL waste disposal effects are shown in Fig. 2. In this diagram, the relationship between product manufacture and subsequent consumer use, reuse preparation (repair, resale, or upgrade), recycling, and disposal are illustrated over several time periods.

Following this pattern, Fig. 3 shows the effects of multiple assembly periods on use, reuse, recycling, and disposal operations over time. Both Figs. 2 and 3 stress that the product assembled in period 1 has subsequent take-back and disassembly effects in periods 2, 3, 4, and so on. Likewise, the product assembled in period 2 has subsequent take-back and disassembly effects in periods 3, 4, 5, and so on. Thus, tracking a product by its assembly period and take-back period is a key conceptual factor.

Figs. 2 and 3 illustrate that the designs chosen for assembly have environmental impacts in subsequent periods. Later, in Section IV, the relationship between the assembly impacts and those in subsequent periods will be captured by a three-dimensional (3-D) product take-back factor.

Because estimation of product take-back quantities is helpful in determining the impact of future EOL activities, take-back estimation is useful to companies conducting life cycle assessments (LCA). LCA is a three step methodology composed of inventory profile, environmental impact assessment, and improvement analysis [12]. The inventory step examines the resources required and wastes generated at all stages of the product life cycle including raw materials acquisition, manufacturing, distribution, use, reuse, recycling, and waste disposal. Companies are trying to clearly quantify and compare the processing materials consumed, energy utilized, solid wastes generated, and pollutants emitted to air and water over the life cycle of a particular product [13]. Materials and energy balance equations are often used to assess the inputs and outputs at each stage in the product life cycle [14]. These are challenging measurements to determine due to the aggregate nature of the available data as well as the availability of data on take-back rates for the different life stages [15]. In order to determine the impacts of the EOL activities for life cycle assessment, the take-back distribution needs to be determined to predict the percentages of take-back. Data are needed to develop plans for reuse, recycling, and disposal of electronic products.

II. Determination of Product Life

Many factors affect product life. Rapidly changing technologies and consumer demands for improvements and leading edge technology may cause product obsolescence. Increased marketing of new enhanced product features has resulted in consumers replacing electronic products before their useful life has expired. Thus, clear definitions for product life based on the various aspects need to be developed.

In this paper, several product life terms are used. These terms differentiate the roles that market place demands, reliability, and storage play in determining the time from manufacture to the time of product take-back. The product life definitions are summarized in Table II.

The final product life is based on several factors including product reliability, advertising and marketing strategy for technological advances, and consumer storage practices. The relationship between these definitions is illustrated in Fig. 4.

The field of product reliability and maintainability is well defined. Statistical methods summarized in [16], [17] to estimate the failure distribution, the mean time to failure (MTTF) and the failure rate may be used to define the reliable product life (Table II).

The determination of product take-back volumes requires more than an estimation of reliable product life. Technological advances often cause electronic products to become obsolete in primary markets even if those products still fulfill the intended function. This leads consumers to replace obsolete product before the end of its useful life. In the past obsolete electronic products have been put into storage or discarded. Today, however, a personal computer (PC) with 286 microprocessors may go to a secondary market or be discarded despite continued reliable function. For the PC market, both hardware advances and new software technologies drive the market product life. For example, although many 14-in spherical-section monitors function properly, primary market dealers recommend current 15-in, 17-in, or 20-in flat panel display monitors for improved display of new software packages [18]. However, substantially more expensive high-resolution 12-in and 13-in monitors may display as much information as a 20-

TABLE II
PRODUCT LIFE DEFINITIONS

Product Life Term	Definition
Reliable product life	The time period from manufacture to the end of product use based on the functional reliability of the product
Market product life	The time period from manufacture to the end of market life due to technical obsolescence
Storage product life	The time period of storage from end of use to end of life activities including reuse, recycling, or disposal
Primary to reuse product life	The time period from manufacture to reuse preparation based on reliable, market, and storage product lives
Final product life	The time period from manufacture to recycling based on reliable, market, storage, and reuse product lives

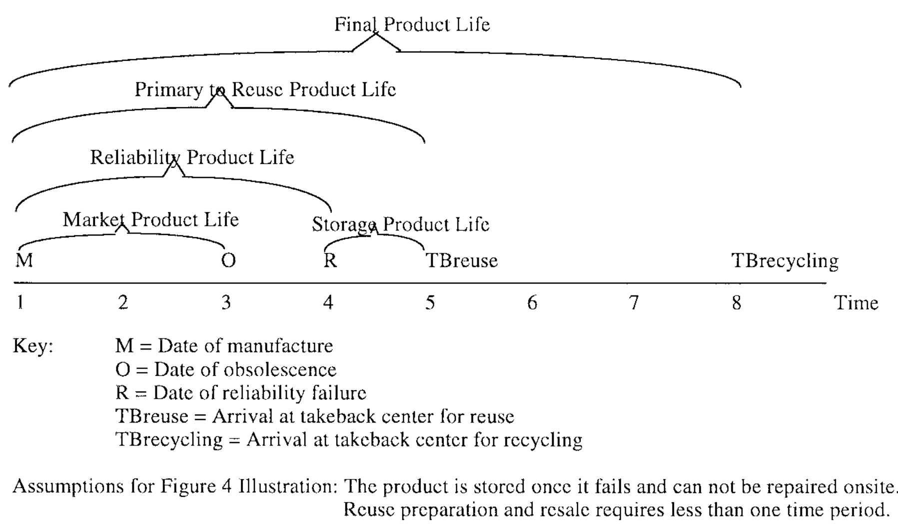

Fig. 4. Illustration of time line for product life.

in monitor. There are new, more sophisticated technologies based on plasma technology or digital micromirror devices that display video images on prototype units that are superior to current monitors [19]. Thus, as evidenced from the PC and computer monitor examples, consideration of market and technology issues are key elements in estimating the final product life.

The storage phenomena for obsolete or nonfunctioning products causes an additional complication in estimating when a product will arrive at take-back centers for reuse or recycling. Storage of obsolete electronics that require repair or upgrade or which are eventually destined for recycling or disposal is common. Published estimates of percentage of computers stockpiled range from 45 to 80% [1]. Determining whether the actual final product life distribution is significantly different than the reliable or market product life distributions is helpful for planning product EOL activities.

III. HISTORICAL PRODUCT LIFE ESTIMATIONS

Product take-back rates for *reuse* actually depend on the *primary* to *reuse product life* while product take-back rates for *recycling* actually depend on the *final product life* defined in Table II. A new framework for estimating product take-back rates for reuse and recycling will be defined in Section IV. In this section, we review product life estimation methods.

In the past, product take-back rates for recycling have been estimated on the basis of pounds of waste per population and on sales volume. Both of these methods and their limitations are reviewed next.

Several sets of estimates for product take-back for recycling are based on calculations of electronic waste per person and population [20], [21]. These figures provide a magnitude of electronic waste for a region. However, for a specific company seeking product take-back rates to evaluate their product life cycle, this aggregate regional measurement can not be used.

Product take-back rates for reuse and recycling are also estimated by examining the annual production and sales rates [7], [22]–[24]. Sarson recommends estimates for take-back rates for reuse and recycling for mature products based on the number sold one product lifetime before [23]. However, Sarson admits that determining the product lifetime is complicated by resale into secondary markets. Still another complication is

TABLE III
PRODUCT TAKE-BACK RATE DEFINITIONS AND NOTATION

$\underline{\beta}_{it\underline{t}}$	the fraction of product design i that is assembled in period t and arrives at a take-back center in period $\underline{t}$ for reuse
$\underline{\underline{\beta}}_{it\underline{\underline{t}}}$	the fraction of product design i that is assembled in period t and arrives at a take-back center in period $\underline{\underline{t}}$ for recycling

that some electronics equipment is never sold due to rapidly changing technologies. In 1994, the Computing Technology Industry Association recommended that resellers be able to return up to 2% unsold equipment to the manufacturer [25]. The phenomenon of industry and consumer storage of obsolete equipment further complicates product take-back rate estimates. Carnegie Mellon recently updated their computer take-back rate estimates based on assumed rates for computer reuse, recycling, stockpiling, or landfilling [1], [26]. Carnegie Mellon's new estimation model assumes that PC's initially have a five-year lifetime and that reused PC's have a three-year lifetime. However, their approach does not reflect the different time spans for technology upgrades that send computers into the reuse market only two to four years after purchase. Nor do they differentiate product lives for newer or more mature technologies.

Other product take-back rates are estimated using ranges such as four to six years for computers. The CARE Vision 2000 Research Initiative uses product take-back ranges [27]. However, ranges and average estimates make plans for product take-back systems difficult and cost analysis even more complicated. For example, it is not known whether 10% of the computer returns are in four years, 70% in five years, and 20% in six years or whether 60% are in four years, 30% are in five years and 10% are in six years.

Various industries estimate their warranty return rates based on current annual production rather than previous annual production quantities. This common product take-back estimation method assumes that manufacturing rates have reached a "steady state" which is appropriate for mature products such as telephone handsets. However, for products with more volatile technology changes, such as personal computers, the framework proposed in the following section should be used.

Another complication in estimating product life is the mechanism for product take-back, storage, sorting, resale, and reclamation. The percentage of responsibility for industry and local government for product take-back operations differs among various countries and even within some countries.

Thus, analysis into the current techniques to estimate product take-back rates, development of more sophisticated product take-back models, and comparison with actual product take-back rates from current take-back activities provide a starting point for estimating product take-back rates.

IV. A New Product Life Estimation Framework

A link between initial manufacturing activities and EOL activities is required in order to more accurately reflect technology maturity, varying obsolescence rates, product life extension activities, and user storage phenomena. The product take-back rate is affected by a variety of phenomena including reliability, marketing trends, technological changes, industry and consumer awareness, participation in product take-back options, the tendency to store expensive obsolete or nonfunctioning products, and stability of take-back infrastructures.

A. Defining the Take-Back Rate

The product take-back rate developed in Table III is a three-dimensional (3-D) measurement which links the assembly time period, $\underline{t}$, and the EOL time period, $\underline{\underline{t}}$. In Table III, a single underline represents reuse (resale, repair, and/or upgrade) and a double underline represents recycling.

As stated in Table III, the take-back rate defines the relationship between design alternative i, assembly period t, and disassembly period t. Because the product take-back rates for reuse and recycling are different, the shape of their distributions are different. In Section IV-B actual product take-back rates for warranty returns are illustrated and in Section IV-C different product take-back rates for reuse and recycling are proposed.

B. Examples from Warranty Returns Data

Actual warranty returns from representative manufacturers were studied for repair claims resulting from product problems. All of the take-back distributions studied were for products assembled 1991 or later and taken back between 1992 and 1996. Fig. 5 shows data for actual useful product lives for four electronics products that have been returned to a take-back center for reuse.

It is clear in Fig. 5 that the return rates for warranty returns vary over time. Although Fig. 5 shows ranges from six months to five years for returns of four different electronics products, it does not differentiate returns for different product maturities. The proposed take-back distribution framework described in Section IV-C captures the change in take-back rates over time for a particular product.

C. Examples of Proposed Take-Back Distribution Framework

The actual product take-back distributions for one of the four electronics products from Fig. 5 are shown in the 3-D graph in Fig. 6. Since the warranty return rates are under 5%, they only constitute a small portion of product take-back for repair and refurbishment. For the data studied, most warranty returns occur in the first two years of the product life.

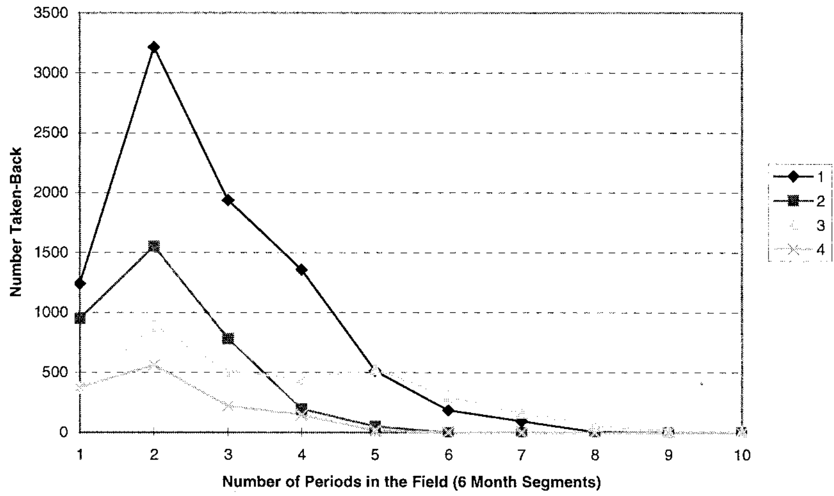

Fig. 5. Warranty returns: Primary to reuse product lives for four electronic products that have been sent to a take-back center for reuse preparation activities.

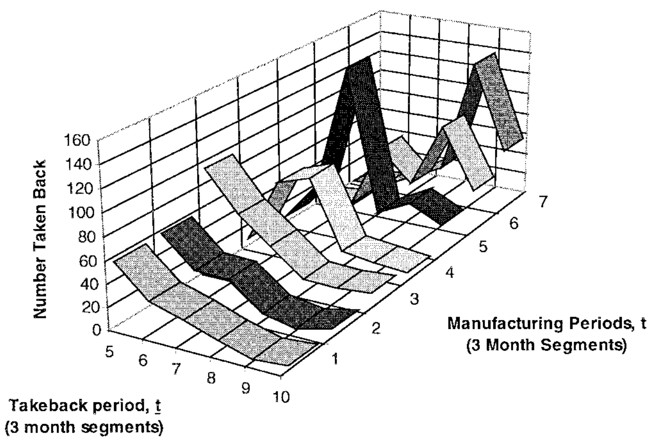

Fig. 6. Actual warranty return take-back distributions for electronics product 4.

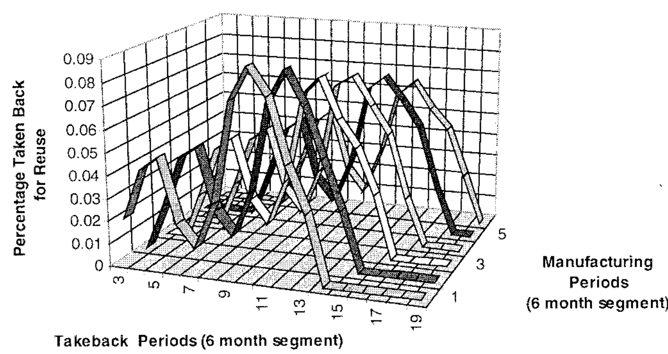

Fig. 7. Example of proposed take-back distribution for reuse.

Technology changes cause another more significant source of take-back. When consumers upgrade to a new model, their previous model may be sent to a repair facility for upgrade and refurbishment for a secondary market if it still functions properly [28], [29]. For this reason, we propose modeling the product take-back rates to a reuse facility as a bimodal distribution to represent the earlier warranty returns and the later technology change returns for upgrade. Thus, a proposed product take-back rate for reuse for a single electronic product is illustrated in Fig. 7. The graph illustrates the relationship between the percentage arriving at the reuse preparation facility from each year of assembly. For products assembled in later periods, the product take-back rates for reuse are less than for products assembled in earlier periods due to obsolescence.

Currently, the benefits of the proposed framework are difficult to validate precisely due to the variability in information technology. For example, as electronic components, subassemblies, and final assemblies progress through the manufacturing and distribution supply chain, different barcodes are used to track different types of product information. When various products arrive at product take-back centers, information such as the date of manufacture is not recorded due to the nonuniformity of the information provided. For this reason, the six product take-back centers contacted by the authors collected data for product take-back by year of manufacture only for warranty returns; data from product take-back centers with date of manufacture data for all products returned was unavailable. Future studies to compare the proposed product take-back rates with actual product take-back rates are needed.

Based on Table II product life definitions, the authors propose that the take-back rate for recycling reflect a gradual increase in the first half of the primary years followed by a rapid increase in the latter final product years due to the technology change, functional failure, and storage release periods. An example of a proposed product take-back rate for recycling for a single high value electronics product (approximately U.S. $2K retail) is illustrated in Fig. 8.

The advantage of this approach to take-back estimations is that it relates three dimensions of take-back: the manufacturing period, the take-back period, and the quantity taken back. Unlike two-dimensional take-back factors, a 3-D take-back distribution over time allows for attributes such as technology maturity, improvements in design modularity, increases in

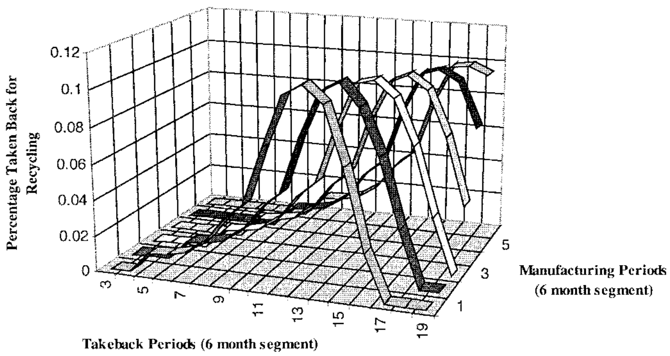

Fig. 8. Example of proposed take-back distribution for recycling.

take-back activities, or changes in storage phenomena to be captured.

V. Conclusions and Applications for Product Life Estimations

The 3-D product take-back framework developed in Section IV reflects the product obsolescence of rapidly changing technologies. For electronics products such as personal computers, modems, and monitors, this framework provides a more complete perspective for determining take-back volumes for EOL planning. The proposed framework estimates take-back based on date of manufacture. However, this framework is limited by nonuniform information technology practices of the past that result in more difficult collection of date of manufacture information. However, barcode-tracking information on newer products and access based on Internet connections may improve future links between EOL operations and original equipment manufacturers.

To determine the effects of varying EOL take-back distributions on cost and product stewardship goals, sensitivity analysis of take-back rates may be studied using the Emerging Product Process and Consideration of Environment (EPPACE) mixed integer programming model in [30]. For example, in case studies of electronic assemblies for telecommunications equipment reported in [31], the product take-back distributions are scaled by factors of 2, 1.5, 0.5, and zero to study how sensitive design selection for profitability maximization is to various product take-back levels.

The product take-back framework developed is not only useful for design selection with life cycle considerations, but also for capacity planning for recycling and EOL centers. As legislation for EOL activities increase, product take-back centers face inventory, scheduling, and processing challenges. With improved understanding of the drivers for product take-back, capacity planning for various product arrivals at product take-back centers can be improved. Current and future research efforts are focused on product take-back center design and planning.

References

[1] J. B. Davis, “Fewer computers landfilled than expected, says study,” in *Product Stewardship Advisor*. Arlington, MA: Cutter Information Corp., 1997, vol. 1:2, pp. 7–8.

[2] J. C. Bullock, “Environmentally sound management of electronic scrap and the basel convention on control of transboundary movements of hazardous waste and their disposal,” presented at *IEEE Int. Symp. Electron. Environ.*, Orlando, FL, 1995.

[3] J. Gamalski, personal communication, 1996.

[4] J. B. Davis, “Is mandated product takeback coming to a country near you?” in *Product Stewardship Advisor*. Arlington, MA: Cutter Information Corp., 1997, vol. 1:1, pp. 2–5.

[5] A. Kulick, “Europe plans to curb electronic, electrical waste,” *World Wastes*, pp. 6–7, 1996.

[6] *Cleaner Technology Action Plan*. Copenhagen, Denmark: Ministry of the Environment, 1992.

[7] J. Hubschman, K. Johnson, J. Ketchum, B. Lundquist, B. Meier, E. Moore, T. Osdoba, S. Andre, and B. Barnum, *Management of Waste Electronic Appliances*. St. Paul MN: Minnesota Office of Environmental Assistance, 1995.

[8] J. B. Davis, “Regulatory and policy trends,” in *Product Stewardship Advisor*. Arlington, MA: Cutter Information Corp., 1997, vol. 1:2, pp. 10–13.

[9] R. D. Mann, “Recycling is dead—Long live asset management,” presented at the *IEEE Int. Symp. Electron. Environ.*, San Francisco, CA, 1997.

[10] “Stewardship in the computers and electronics sector,” presented at *EPR2—Electron. Product Recovery Recycling Conf.*, Washington, DC, 1997.

[11] M. K. Low, D. J. Williams, and C. Dixon, “The economics of end of life management strategy choice: Routes to revenue generation from mature products,” presented at *IEEE Int. Symp. Electron. Environ.*, 1997.

[12] SETAC, “Guidelines for life-cycle assessment: A code of practise,” presented at *SETAC Workshop*, Sesimbra, Portugal, 1993.

[13] T. E. Graedel and B. R. Allenby, *Industrial Ecology*. Englewood Cliffs, NJ: Prentice-Hall, 1995.

[14] B. W. Vigon, D. A. Tolle, B. W. Cornaby, H. C. Latham, C. L. Harrison, T. L. Boguski, R. G. Hunt, J. D. Sellers, and M. A. Curran, *Life-Cycle Assessment: Inventory Guidelines and Principles*. Cincinnati, OH: EPA, 1993.

[15] J. A. Stuart, L. J. Turbini, and J. C. Ammons, “The implications of activity based environmental impact allocation,” presented at *IEEE Int. Symp. Electron. Environ.*, 1996.

[16] R. E. Barlow and F. Proschan, *Statistical Theory of Reliability and Life Testing*. New York: Holt, Rinehart, & Winston, 1975.

[17] K. C. Kapur, “Reliability and maintainability,” in *Handbook of Industrial Engineering*, G. Salvendy, Ed., 2nd ed. New York: Wiley, 1992, pp. 2315–2348.

[18] W. Crawford, “The big picture: Choosing your next monitor,” *Online*, pp. 93–97, 1995.

[19] S. H. Wildstrom, “Passing the screen test,” in *Business Week*, p. 16, 1996.

[20] D. P. Bashford, “Survey on the implications for recycling electronic and electrical equipment,” ERA 93-1003R, 1993.

[21] S.-O. Taberman, B. Carlsson, H. Erichsen, J. B. Legarth, and J. Gregersen, “Environmental consequences of incineration and landfilling of waste from electr(on)ic equipment,” in *TemaNord 1995:555*. Copenhagen, Denmark: Nordic Council of Ministers, 1995.

[22] “Waste 92—End of life electronic equipment,” ENEA, Study Contract, National Agency for New Technology, Energy, and the Environment, European Union, 1993.

[23] S. C. Sarson, *The Recycling of Electronic Scrap*. Hertfordshire, U.K.: Warren Spring Laboratory, 1992.

[24] K. B. Young, “Product return rates,” *Quality*, pp. 38–41, 1988.

[25] J. Longwell, “CTIA sets product-return gidelines,” in *Comput. Reseller News*, p. 10, 1994.

[26] H. S. Matthews, “Carnegie Mellon updates computer disposition data,” *EPR2 Update*, pp. 1, 3, 1997, 1997.

[27] L.-G. Scheidt, “International coordination secretariat of CARE vision 2000 electronics recycling,” *Personal Communication*, 1995.

[28] T. Aeppel, “For recyclers, old computers offer new niche,” in *Wall Street J.*, pp. B1–B2, 1994.

[29] E. Worden, “Recyclers diversify to keep ahead as precious metal recoveries slide,” in *Amer. Metal Market*, vol. 103, p. 8A, 1995.

[30] J. A. Stuart, J. C. Ammons, and L. J. Turbini, “A product and process selection model with multidisciplinary environmental considerations,” *Operat. Res.*, to be published.

[31] J. A. Stuart, L. J. Turbini, and J. C. Ammons, "Investigation of electronic assembly design alternatives through production modeling of life cycle impacts, costs, and yield," *IEEE Trans. Comp., Packag., Manufact. Technol.,* vol. 20, pp. 317–326, Oct. 1997.

Julie Ann Stuart received the M.S. and Ph.D. degrees in industrial and systems engineering from the Georgia Institute of Technology, Atlanta.

She is an Assistant Professor in the Department of Industrial, Welding, and Systems Engineering, The Ohio State University, Columbus. Her research and teaching interests include production modeling, facilities planning and design, environmentally conscious design and manufacturing, and electronics assembly and disassembly.

Dr. Stuart is a member of ASQ, IIE, INFORMS, and SME. She is an Ameritech Faculty Fellow and an NSF/Lucent Technologies Industrial Ecology Faculty Fellow.

Ming Kaan Low received the B.Eng. degree in engineering from the National University of Singapore and the M.Sc. and Ph.D. degrees from Loughborough University, Loughborough, U.K.

He is a Research Associate with the Department of Manufacturing Engineering, Loughborough University. His current work addresses the creation of holistic models of the product life cycle that embrace the two key business drivers of economics and environmental impact and support the generation of product design concepts aimed at achieving step changes in reduction of environmental impact. He has worked with Maxtor, the Housing Development Board of Singapore and the Singapore Army.

David J. Williams (M'88) received the B.Sc. degree from UMIST, Manchester, U.K., and the Ph.D. degree from Cambridge University, Cambridge, U.K.

He has been Professor of Manufacturing Processes, Loughborough University, Leicestershire, U.K., since 1989. He is now Director of the PRIME Faraday Partnership. He was Head of the Department of Manufacturing Engineering from 1991 to 1995. His present research focuses on the resolution of problems within electronics manufacturing, ranging from the level of process engineering science to business globalization. This electronics process work follows a number of years of control-oriented research in the area of computer integrated manufacturing. Before taking up his present post, he was Lecturer in manufacturing engineering and design at Cambridge University, Cambridge, U.K., and worked for Metal Box and GKN. He has published three books and more than 200 papers.

Dr. Williams is Editor-in-Chief of the *International Journal of Computer Integrated Manufacturing* and the *Journal of Electronics Manufacturing*, and is an active consultant to the manufacturing industry and several governments.

Laura J. Turbini (SM'98) received the M.S. and Ph.D. degrees in inorganic chemistry from Cornell University, Ithaca, NY.

She is presently a Professor of Materials Science and Engineering, Georgia Institute of Technology, Atlanta. Her research interests include interconnection technology with an emphasis on soldering fluxes, cleaning, and reliability, and development of test methods to evaluate the effects of processing materials using accelerated life testing. She joined Western Electric Engineering Research Center (now Lucent Technologies Bell Labs) in 1977 and became the Research Leader in Soldering in 1979. She became an Engineering Manager at the AT&T manufacturing plant, Denver, CO. She joined the Georgia Institute of Technology in 1989 as the Associate Director of the Manufacturing Research Center.

Dr. Turbini served as Editor of the *Western Electric Engineer* from 1982 to 1985.

Jane Chumley Ammons received the Ph.D. degree in industrial and systems engineering from the Georgia Institute of Technology, Atlanta.

She is an Associate Professor of industrial and systems engineering at the Georgia Institute of Technology, where she teaches and performs research in the areas of production system design and analysis with a focus on electronics assembly systems; and total quality, with applications in education and manufacturing. She has authored or coauthored numerous technical papers, book chapters, and presentations on topics in the areas of electronic assembly systems, environmentally conscious manufacturing, apparel manufacturing, material handling, electric generation capacity planning, flexible manufacturing and flexible assembly systems, quality, and total quality.

Dr. Ammons received several research and teaching awards, and developed the first NSF Engineering Education Scholars Workshop. She is a member of SME, INFORMS, IIE, and ASEE. She serves in a leadership role on a number of national boards and panels related to her professional activities.