

January 01, 2004

Sensor-embedded computers for better life-cycle management

Sagar V. Kamarthi
Northeastern University

Surendra M. Gupta
Northeastern University

Zeid Ibrahim
Northeastern University

Vadde Srikanth
Northeastern University

Recommended Citation

Kamarthi, Sagar V.; Gupta, Surendra M.; Ibrahim, Zeid; and Srikanth, Vadde, "Sensor-embedded computers for better life-cycle management" (2004).. Paper 102. <http://hdl.handle.net/2047/d10003423>



Laboratory for Responsible Manufacturing

Bibliographic Information

Vadde, S., Kamarthi, S. V., Gupta, S. M. and Zeid, I., "Sensor-Embedded Computers for Better Life-Cycle Management", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing IV***, Philadelphia, Pennsylvania, pp. 256-263, October 26-27, 2004.

Copyright Information

Copyright 2004, Society of Photo-Optical Instrumentation Engineers.

This paper was published in Proceedings of SPIE (Volume 5583) and is made available as an electronic reprint with permission of SPIE. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited.

Contact Information

Dr. Surendra M. Gupta, P.E.
Professor of Mechanical and Industrial Engineering and
Director of Laboratory for Responsible Manufacturing
334 SN, Department of MIE
Northeastern University
360 Huntington Avenue
Boston, MA 02115, U.S.A.

(617)-373-4846 **Phone**
(617)-373-2921 **Fax**
gupta@neu.edu **e-mail address**

<http://www.coe.neu.edu/~smgupta/> **Home Page**

Sensor Embedded Computers for Better Life Cycle Management

Srikanth Vadde, Sagar V. Kamarthi*, Surendra M. Gupta, Ibrahim Zeid
Laboratory for Responsible Manufacturing
334 SN, Department of MIE
Northeastern University
360 Huntington Avenue
Boston, MA, 02115 USA

ABSTRACT

This research investigates the advantages offered by embedded sensors for cost-effective and environmentally benign product life cycle management for desktop computers. During their use by customers as well as at the end of their lives, Sensor Embedded Computers (SECs) by virtue of sensors embedded in them generate data and information pertaining to the conditions and remaining lives of important components such as hard-drive, motherboard, and power supply unit. A computer monitoring framework is proposed to provide more customer comfort, reduce repair costs and increase the effectiveness of current disassembly practices. The framework consists of SECs, remote monitoring center (RMC), repair/service, disassembly, and disposal centers. The RMC collects dynamic data/information generated by sensors during computer usage as well as static data/information from the original equipment manufacturers (OEMs). The RMC forwards this data/information to the repair/service, disassembly, and disposal centers on need-basis. The knowledge about the condition and remaining life of computer components can be advantageously used for planning repair/service and disassembly operations as well as for building refurbished computers with known expected lives. Simulation model of the framework is built and is evaluated in terms of the following performance measures: average downtime of a computer, average repair/service cost of a computer, average disassembly cost of a computer, and average life cycle cost of a computer. Test results show that embedding sensors in computers provides a definite advantage over conventional computers in terms of the performance measures.

Keywords: sensor integrated computers, embedded sensors, product life cycle management, repair, disassembly.

1. INTRODUCTION

The primary objective of this research is to evaluate the effectiveness of on-line monitoring of computer components by means of embedded sensors. The embedded sensors will monitor the health of computer components to predict imminent computer/component failures, assist repair/service personnel in quickly diagnosing reasons for computer failures, and estimate the remaining life of computer components. Advances in the field of sensors, microprocessors, and communication technologies offer tools necessary to transform the traditional reliability approach to on-line condition assessment of computers.

Traditional reliability engineering methods provide failure characteristics of components that are taken into consideration at the product manufacturing stage. But those characteristics are of little use beyond the manufacturing stage. Once products are delivered to customers, different product units are exposed to different working conditions and different usage patterns which render the traditional reliability estimates provided by product manufacturers invalid. Consider a computer hard-drive that crashes 6 months after its purchase, much before its expected life of 7 years. In this situation the manufacturer's estimate of the expected life cannot provide much comfort to the customer. In contrast some computer components may remain in good working condition even beyond their expected life.

When computers fail, diagnosing the exact reason for failure can be difficult. This can lead to increased repair time and added repair costs. Also at the end of lives of computers when they are sent to a disassembly facility, existing disassembly techniques use little or no prior knowledge about their condition and remaining life. Thus the existing disassembly practices often fail to categorize computer components according to their remaining lives.

* Corresponding author, contact at sagar@coe.neu.edu, 617-373-3070.

2. RELATED WORK

This section reviews the published literature on on-line product condition monitoring and product recovery. The idea of collecting data from products during their usage was first proposed by Scheidt *et al.*¹ and subsequently advocated by Klausner *et al.*^{2, 3, 4}, Karlsson⁵, Masui *et al.*⁶, and Petriu *et al.*⁷. They propose to embed into products the devices that have memory to record parameters of interest that are generated during the product usage. In the context of industrial recycling of electric motors, Karlsson *et al.*⁵ proposed a distributed sensor system and described a method for performing sensor fusion for effective recycling of electric motors. Klausner *et al.*⁴ presented an information system for product recovery that combines data from embedded sensors with demand and prices information in a second hand market. In a recent report Rasche⁸ noted that the current sensor market is leaning towards the development of communication features in products to facilitate data transmission over a network. For related papers in the area of product recovery, see the survey paper by Gungor and Gupta⁹.

3. EFFECTIVE LIFE CYCLE MANAGEMENT OF COMPUTERS

3.1 Sensor embedded computers (SECs)

SECs contain sensors implanted at the time of their production to monitor their critical components. By facilitating data collection during computer usage, these embedded sensors enable one to predict computer/component failures and estimate the remaining life of components as the computers reach their end of lives (EOL).

3.3 Computer monitoring framework

The authors propose a computer monitoring framework that interlinks SECs, remote monitoring center (RMC), repair/service center, disassembly center, remanufacturing center, and disposal center for a cost-effective and environmentally benign life cycle management of computers, see Figure 1. The functions and characteristics of each entity in the framework are presented below.

3.3.1 Remote monitoring center (RMC)

The RMC stores static data/information compiled by OEMs during the computer manufacturing stage¹⁰ and dynamic data/information generated by sensors in SECs during the period of their usage. Static data/information consists of the bill of materials, component suppliers, configuration options, servicing instructions, and EOL guidelines such as disassembly sequence². Much of this data is stored at the RMC in a database against a unique identification code. Dynamic data generated during the use of a computer consists of sensor data, patterns of usage, number of use cycles, runtime in each use cycle, and environmental conditions. Dynamic data also includes service history on inspections, parts replaced and repaired^{2, 3}. The dynamic data is transmitted to the RMC via a communication network, either continuously or intermittently on an hourly, or daily, or weekly, or monthly basis depending on the computer usage pattern. On intermittent basis, sensors can send data generated during every cycle of the computer's operation or can send statistics of the measured data to the RMC¹¹. To transmit the data/information to the RMC, sensors can use an on-board radio-frequency transmitter, telephone line, or the Internet.

The RMC facilitates better life cycle management of computers by providing the stored data/information to the customers, repair/service, disassembly, and disposal centers. Wireless communication technologies, satellite links, and the Internet act as enablers for the RMC to receive and transmit data/information from geographically remote computers.

3.3.2 Repair/service center

Customers bring their computers to the repair/service center when they are predicted to fail or if they are malfunctioning. The repair/service personnel can request the static and dynamic data of the computer from the RMC to find out its condition and associated reasons for its failure. Depending on the reasons for failure, the service personnel can perform maintenance or can replace defective components with either refurbished or new components. The repair/service center communicates the failure and repair history to the RMC for record keeping.

3.3.3 Disassembly center

When computers reach their EOL, their users hand them over to disassembly centers. These EOL computers are disassembled according to disassembly plans scripted by the remaining lives of computer components which are estimated from dynamic data/information stored at the RMC. At the remanufacturing center, refurbished computers are built with components that have similar remaining lives and are sold in second hand markets. The recovered components

that have negligible remaining lives are sent to disposal centers where they are disposed off based on the static data/information obtained from the RMC.

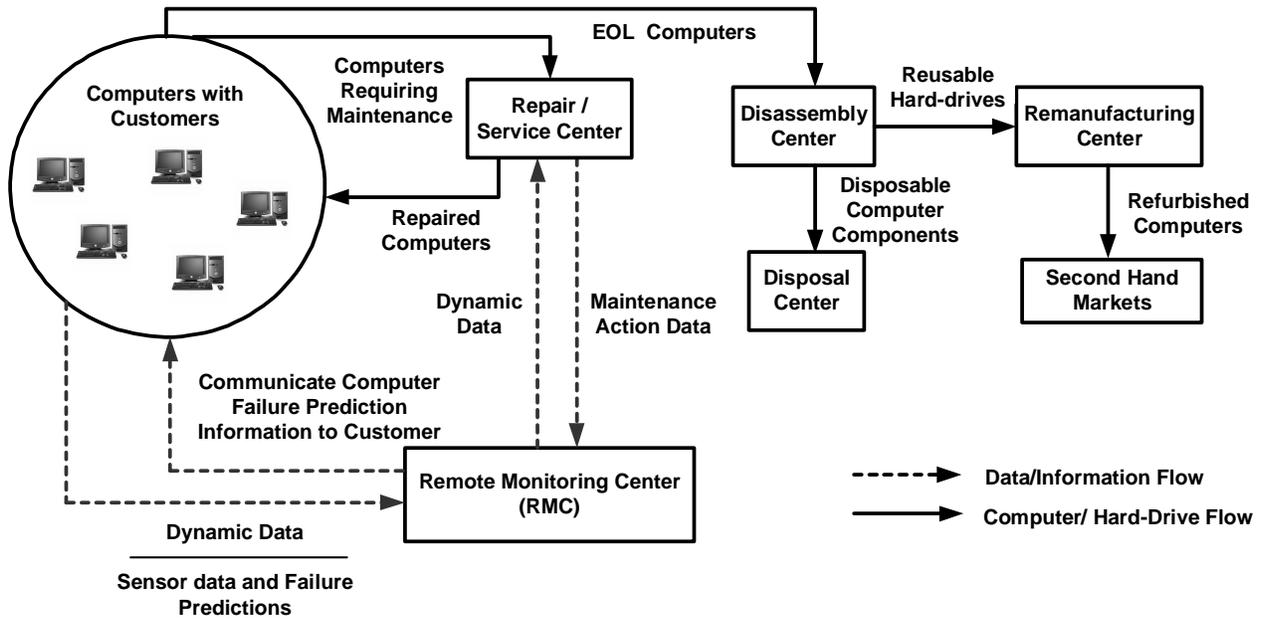


Figure 1: Computer monitoring framework

3.4 Conceived benefits from computer monitoring framework

Sensors can have significant positive impact on the life cycle management of computers. Marketing advantage can be gained by extracting patterns of consumer use from the stored data at the RMC. Embedded sensors can enhance reliability, maintainability, serviceability, recyclability, and promote design improvements in each subsequent generation of computers. Table 1 lists the advantages of SECs over normal computers.

Table 1: Advantages of SECs over normal computers

Factor	SECs	Normal Computers
Percentage of computers accurately predicted to fail	High	Low
Time required to diagnose and repair computers	Short	Long
Cost of repairing computers	Low to medium	Medium to high
Warranty period on refurbished computers	Medium to long	Short
Longevity of computers	Beyond expected life in some cases	May reach expected life
Percentage of surprise computer failures	Low	High
Life cycle cost	Low	Medium

4. SIMULATION MODEL

Simulation model of the computer monitoring framework is built in Java. The simulation model considers a scenario where a set of ten thousand sensor embedded desktop computers are being used by users and managed by their supervisor.

In order to evaluate the effectiveness of embedding sensors in computers, the performance measures in the two scenarios – with embedded sensors (SECs) and without embedded sensors (normal computers) – are compared. The assumptions, policies, and parameters used in the simulation models representing the two scenarios are presented in Table 2.

Table 2: Simulation model assumptions, policies and parameters

	Sensor Embedded Computers	Normal Computers
Assumptions	Failure rate of computers is 1% per year.	Same
	Computer failures are caused only due to the gradual degradation and eventual breakdown of their hard-drives.	Same
	Failure predictions by sensors are deterministic.	n/a
	Computers are as good as new after repair/service.	Same
	The components recovered at the disassembly center are good for building refurbished computers at the remanufacturing center.	Only 50% of the recovered components are good for building refurbished computers.
	All refurbished computers built are sold in second hand markets. The revenue earned from the sale (<i>PRC</i>) is computed as the number of refurbished computers sold times the cost of a refurbished computer.	Same
Policies	Hard-drive failures are of Type 1 and Type 2. Type 1 failures are repairable whereas Type 2 failures are catastrophic hard-drive crashes. In Type 2 failures data on the hard-drive is wiped out completely warranting a replacement of the hard-drive. Sensors can predict 80% of Type 1 and Type 2 failures. The 80% Type 2 failures detected by sensors results in no hard-drive data loss but still warrants a hard-drive replacement. False sensor alarm rate is 5%.	Same except that hard-drive failures cannot be predicted because of the absence of sensors.
	The repair/service cost (<i>RSC</i>) of a computer comprises of a fixed cost (C_1) to attend to a service call, and an additional labor cost (C_2) for maintenance work. Total repair/service cost, $RSC = C_1 + C_2$.	Same
	A computer reaches its EOL at the end of 6 years at which point it is sent to the disassembly center.	Same
	At the disassembly center 70% of the EOL computers are disassembled. The other 30% are assessed as worthless for recovering reusable components	At the disassembly center 100% of the EOL computers are disassembled.
	Cost of disassembly (<i>DAC</i>) is computed from the hourly disassembly labor rate.	Cost of disassembly (<i>DAC</i>) is the sum of the disassembly labor cost and the cost to analyze the recovered components for reusability.

Table 2 (continued)

Parameters	Expected life of a computer is 6 years and that of a hard-drive is 7 years.	Same
	Cost of a new computer is (PC) = \$1225.	Cost of a new computer is (PC) = \$1200.
	Cost of a refurbished computer = \$400.	Cost of a refurbished computer = \$250
	Overhead cost of maintaining the RMC center (OH) = \$10,000 per year.	n/a
	Cost of a new hard-drive = \$100.	Same
	Repair/service cost (C_1) = \$25, and labor cost for repair = \$50 per hour.	Same
	Average time to repair a Type 1 failure that is undetected by sensors = 4 hours	Average time to repair a Type 1 failure = 4 hours.
	Average time to repair a sensor predicted Type 1 failure = 2 hours.	n/a
	Average time to replace a hard-drive in case of Type 2 failures = 4 hours.	Same
	Average time spent at the repair/service center (including repair time) by a computer is 1 day and 4 days in case of sensor predicted Type 1 and Type 2 failures respectively. In case of sensor failing to detect a failure, it takes 4 days and 7 days for Type 1 and Type 2 failures respectively.	Average time spent at the repair/service center by a computer is 4 days in case of Type 1 failure, 7 days in case of Type 2 failure. This includes the repair time of the computer.
	Revenue loss because of downtime of a computer = \$50 per day.	Same
	Revenue loss is \$600 per computer for undetected catastrophic computer failures (Type 2).	Revenue loss because of wiped out data and the amount spent to recover it is \$600 per computer. This occurs in a catastrophic computer failure (Type 2).
	Revenue lost due to a false sensor alarm = \$50 per computer.	n/a
	Disposal cost of a computer incurred by the office (DC) = \$50.	Same
Labor cost of disassembly = \$25 per hour.	Same	
No cost involved to analyze the recovered components for reusability because sensors provide their remaining life information prior to disassembly.	Cost to analyze the reusability of recovered components = \$50.	

The following are the performance measures to evaluate the two simulation models:

- Average life cycle cost of a computer, $ALCC = (PC + RSC + DC + DAC + OH - PRC)/n$, where n is the number of computers in the office.
- Average repair/service cost of a computer = RSC/n .
- Average disassembly cost of a computer = DAC/n .
- Average downtime of a computer is the average time the computer is held at the repair/service center.

4.1 Simulation Results

The two simulation models are run with run lengths of 1, 2, ... 6 years. Each simulation run is independent of the previous run. For a given simulation run length, 20 replicated runs are performed. Tables 3, 4, 5, and 6 list the average values of these 20 replication runs.

Table 3: Simulation results for sensor embedded computers

Year	Sensor predicted failures (Type 1)	Sensor predicted failures (Type 2)	Unexpected repairable failures (Type 1)	Unexpected catastrophic failures (Type 2)	False sensor alarms	Loss due to false sensor alarms (\$)	Loss due to downtime per computer (\$)	Loss due to catastrophic failures per computer (\$)
1	475	73	111	15	38	1,915.00	5.50	0.35
2	961	156	249	35	75	3,767.00	12.15	1.55
3	1520	226	372	51	111	5,597.00	18.65	2.60
4	2038	288	492	70	152	7,627.00	24.85	3.85
5	2534	358	652	94	195	9,787.00	32.15	5.15
6	3025	432	755	101	236	11,847.00	37.55	5.60

Table 4: Simulation results for normal computers

Year	Unexpected repairable failures (Type 1)	Unexpected catastrophic failures (Type 2)	Loss due to downtime per computer (\$)	Loss due to catastrophic failures per computer (\$)
1	524	150	15.20	8.50
2	1061	304	31.25	17.85
3	1586	442	46.70	26.05
4	2091	606	62.40	35.85
5	2642	745	78.45	44.20
6	3184	913	95.05	54.35

Table 5: Performance measures for sensor embedded computers

Year	Average downtime per computer (days)	ALCC per computer (\$)	Average disassembly cost per computer (\$)	Repair cost per computer (\$)
1	0.12	-	-	11.45
2	0.26	-	-	24.07
3	0.39	-	-	36.70
4	0.52	-	-	48.63
5	0.67	-	-	61.59
6	1.49	1,071.99	4.38	72.75

Table 6: Performance measures for normal computers

Year	Average downtime per computer (days)	ALCC per computer (\$)	Average disassembly cost per computer (\$)	Repair cost per computer (\$)
1	0.31	-	-	16.69
2	0.63	-	-	33.76
3	0.94	-	-	50.07
4	1.26	-	-	66.76
5	1.58	-	-	3.68
6	2.58	1,243.57	9.01	101.33

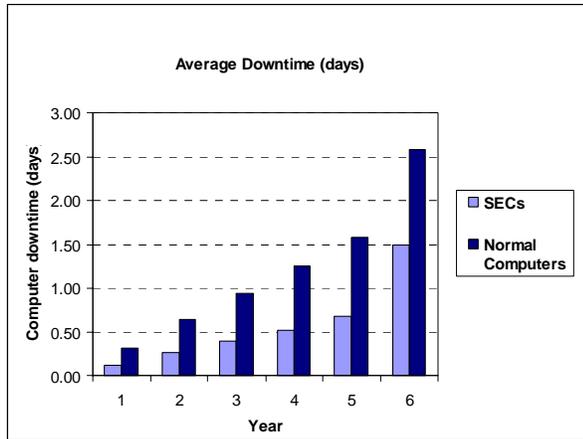


Figure 2: Average downtime of a computer.

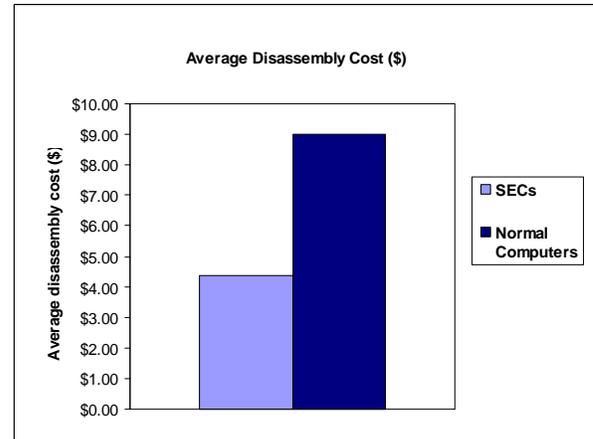


Figure 4: Average disassembly cost of a computer.

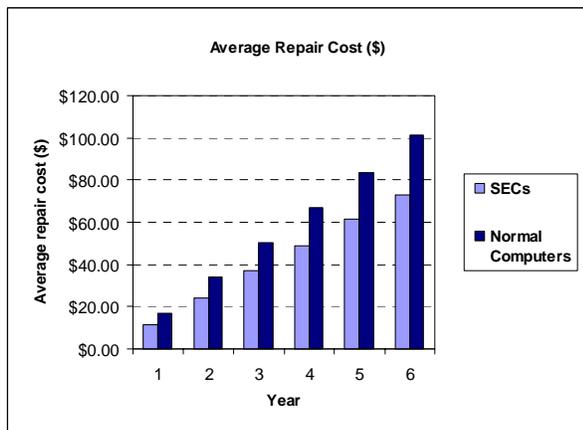


Figure 3: Average repair cost of a computer.

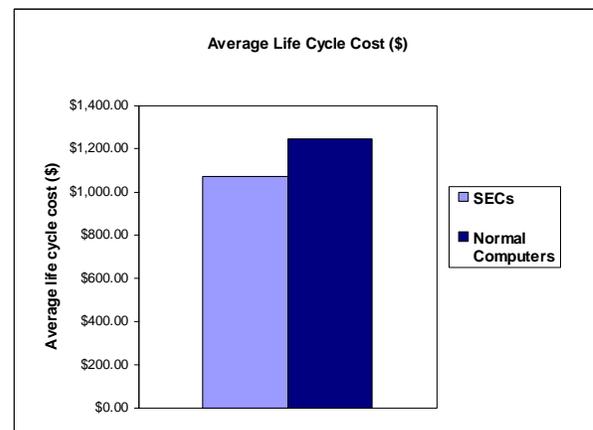


Figure 5: Average life cycle cost of a computer.

Figure 2, 3, 4, and 5 compare the performance measures for the two simulation models. As shown in Figures 2 and 3 the average downtime and average repair cost of a computer is lower for the case of SECs because sensors can pinpoint the exact reasons for computer failures which reduces the repair time and hence the downtime. As can be observed in Figure 4 the disassembly cost is lower for the case of SECs because (a) only those computers whose components have substantial remaining life are disassembled, and (b) no additional cost is required to estimate the reusability of recovered components since the remaining life is already known before disassembly. In Figure 5 the average life cycle cost of a computer is lower for the case of SECs because of low repair and disassembly costs. These results support the authors' belief that embedded sensors provide significant advantage during computer's usage period and at their end-of-life.

5. CONCLUSIONS

Sensors implanted in computers can perform better on-line health monitoring of their components, predict their failures, and provide data to estimate their remaining lives. A computer monitoring framework that interconnects SECs, RMC, repair/service center, disassembly center and disposal center for data/information exchange is investigated. The RMC stores the huge amount of data/information generated by embedded sensors, servicing data/information from repair/service center, and communicates with the computer users about imminent computer failures. Data/information stored at the RMC can assist repair/service personnel in diagnosing computer failures. At the EOL of computers data/information from RMC can be used to reliably estimate the remaining lives of computers and their components. The remaining life information can be used to develop better disassembly plans that selectively recover components with substantial life and make refurbished computers from recovered components that have similar remaining lives. Simulation results affirm that sensors reduce repair time, repair costs, disassembly cost, and average life cycle cost.

These factors contribute to improved customer satisfaction and an environmentally benign life cycle management of computers.

REFERENCES

1. L. G. Scheidt and S. Zong, "An Approach to Achieve Reusability of Electronic Modules", *Proceedings of the IEEE International Symposium on Electronics and the Environment*, pp. 331-336, 1994.
2. M. Klausner, W. M. Grimm, C. Hendrickson, and A. Horvath, "Sensor-Based Data Recording of Use Conditions for Product Takeback", *Proceedings of IEEE International Symposium on Electronics and the Environment*, pp. 138-143, 1998.
3. M. Klausner, W. M. Grimm, and C. Hendrickson, "Reuse of Electric Motors in Consumer Products", *Journal of Industrial Ecology*, vol. 2, no. 2, pp. 89-102, 1998.
4. M. Klausner and W. M. Grimm, "Integrating Product Takeback and Technical Service", *Proceedings of the 1999 IEEE International Symposium on Electronics and Environment*, pp. 48-53, 1999.
5. B. Karlsson, "A Distributed Data Processing System for Industrial Recycling", *Proceedings of IEEE Instrumentation and Measurement Technology Conference*, vol. 1, pp. 197-200, 1997.
6. K. Masui, K. Mizuhara, K. Ishii, and C. M. Rose, "Development of Products Embedded Disassembly Process Based on End-of-Life Strategies", *Proceedings of EcoDesign*, pp. 570-575, 1999.
7. E. M. Petriu, N. D. Georganas, D. C. Petriu, D. Makrakis, and V. Z. Groza, "Sensor-Based Information Appliances", *IEEE Instrumentation and Measurement Magazine*, vol. 3, no. 4, pp. 31-35, 2000.
8. M. Rasche, "Sensors: Bringing the World of Tomorrow...Today", *Appliance*, pp. 37-38, December 2003.
9. A. Gungor and S. M. Gupta, "Issues in Environmentally Conscious Manufacturing and Product Recovery: A Survey", *Computers and Industrial Engineering*, vol. 36, no. 4, 811-853, 1999.
10. M. Simon, G. Bee, P. Moore, J-S. Pu, and C. Xie, "Modelling of the Life Cycle of Products with Data Acquisition Features", *Computers in Industry*, vol. 45, pp. 111-122, 2001.
11. A. Schmidt and K. V. Laerhoven, "How to Build Smart Appliances?", *IEEE Personal Communications*, vol. 8, no. 4, pp. 66-71, 2001.