IRis

Northeastern University

Mechanical and Industrial Engineering Faculty Publications

Department of Mechanical and Industrial Engineering

January 01, 2010

An evaluation of the effect of sensor embedded products in product disassembly with precedence relationships

Mehmet Ali Ilgin
Northeastern University

Surendra M. Gupta
Northeastern University

Recommended Citation

Ilgin, Mehmet Ali and Gupta, Surendra M., "An evaluation of the effect of sensor embedded products in product disassembly with precedence relationships" (2010). *Mechanical and Industrial Engineering Faculty Publications.* Paper 1. http://hdl.handle.net/2047/d20000249

This work is available open access, hosted by Northeastern University.

Laboratory for Responsible Manufacturing

Bibliographic Information

Ilgin, M. A. and Gupta, S. M., "An Evaluation of the Effect of Sensor Embedded Products in Product Disassembly with Precedence Relationships", ***Proceedings of the 2010 Northeast Decision Sciences Institute Conference***, Alexandria, Virginia, pp. 409-414, March 26-28, 2010.

Copyright Information

Copyright 2010, Surendra M. Gupta.

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***

AN EVALUATION OF THE EFFECT OF SENSOR EMBEDDED PRODUCTS IN PRODUCT DISASSEMBLY WITH PRECEDENCE RELATIONSHIPS

Mehmet Ali ILGIN, Northeastern University, Boston, MA 02115, 617-373-7635, ilgin.m@neu.edu
Surendra M. GUPTA, Northeastern University, Boston, MA 02115, 617-373-4846, gupta@neu.edu

ABSTRACT

A promising solution approach to deal with the uncertainty associated with disassembly yield is sensor embedded products (SEPs) which involve sensors implanted during the production process. This study presents a quantitative assessment of the impact of SEPs on the various performance measures of a kanban-controlled air conditioner disassembly line. First, separate design of experiments studies based on orthogonal arrays are carried out for the cases with and without SEPs. Then, the results of paired-t tests comparing two cases based on different performance measures are presented.

1. INTRODUCTION

Disassembly is an important process in product recovery since it allows for the selective separation of desired parts and materials. Due to its high productivity and suitability for automation, disassembly line is the most suitable layout for disassembly operations. A disassembly line inherits more uncertainty compared to an assembly line. The quality, quantity and arrival time of components used in the stations of an assembly line can be controlled by imposing strict conditions on component suppliers. However, there are no such strict conditions on the quality, quantity and arrival time of end-of-life (EOL) products which are dismantled into components through a disassembly line. This increases the uncertainty associated with the condition of the components to be disassembled from EOL products (Ilgin and Gupta [2]).

The use of sensor embedded products (SEPs) is a promising approach to deal with the uncertainty in disassembly yield. SEPs involve sensors implanted during the production process. By monitoring critical components of a product, these sensors facilitate the data collection process. The data collected through sensors can be used to predict the component or product failures during product lives while allowing for accurate estimation of remaining lives and conditions of components at the EOL phase. Moreover, the information provided by sensors regarding any defective, replaced or missing component prior to disassembly of an EOL product provides important savings in testing, disassembly, disposal, backorder and holding costs.

There is a vast amount of literature on the use of sensor-based technologies on after-sale product condition monitoring. Starting with the study of Scheidt and Shuqiang [7], different methods of data acquisition from products during product usage were presented by the researchers (Karlsson [3]; Klausner, et al. [5]; Petriu, et al. [6]). In all of these studies, the main idea is the use of

devices with memory to save monitoring data generated during the product usage. Although most of these studies focus on the development of SEP models, only few researchers presented a cost-benefit analysis. Klausner, et al. [4] analyzed the trade-off between the higher initial manufacturing cost caused by the use of an electronic data log in products and cost savings from the reuse of used motors. Simon, et al. [8] improved the cost-benefit analysis of Klausner, et al. [4] by considering the limited life of a product design. They showed that, in that case, servicing provides more reusable components compared to EOL recovery of parts. Vadde, et al. [10] investigated the effectiveness of embedding sensors in computers by comparing several performance measures in the two scenarios-with embedded sensors and without embedded sensors. The performance measures considered include average life cycle cost, average maintenance cost, average disassembly cost, and average downtime of a computer. However, they do not provide a quantitative assessment of the impact of SEPs on these performance measures. Moreover, since only one component of a computer (hard disk) was considered, the disassembly setting does not represent the complexity of a disassembly line which is generally used to disassemble EOL computers. By extending Vadde, et al. [10], Ilgin and Gupta [1] analyzed the effect of SEPs on the performance of an EOL computer disassembly line which is used to disassemble three components from EOL computers, namely, memory, hard disk and motherboard. Due to relatively simple structure of an EOL computer, they did not consider the precedence relationships among the components. However, disassembly of a particular component is restricted by one or more components in some products. That is why, these products are disassembled according to a route determined based on the precedence relationships.

In this study, we extend Ilgin and Gupta [1] by investigating the quantitative impact of SEPs in case of product disassembly with precedence relationships. Specifically, we consider a kanban controlled air conditioner (AC) disassembly line since an AC involves several precedence relationships among its components. Separate design of experiments (DOE) studies based on orthogonal arrays are performed for the cases with and without SEPs. In the calculation of various performance measure values under different experimental conditions, detailed discrete event simulation models of both cases are used. Then, the results of paired-t tests comparing two cases based on different performance measures are presented.

2. SYSTEM DESCRIPTION

We consider a six-station EOL AC disassembly line. The components disassembled at different stations and the precedence relationships among the components can be seen in Table 1. Although an AC consists of nine components, there is a customer demand for only four components, namely, control box, motor, fan and compressor. Disassembly times at stations, demand inter-arrival times for components and EOL AC inter-arrival times are all exponentially distributed. A conventional AC visits all stations. Following the disassembly at each station, components are tested. The testing times are normally distributed with the means and standard deviations presented in Table 2. A sensor embedded AC visits only the stations which are responsible for the disassembly of functional components and predecessor components of these components. Moreover, following the disassembly of a component, there is no testing operation due to sensor information on the condition of the component.

A small truck with a load volume of 425 cubic feet is used to dispose of excess product, subassembly and components. Whenever the total volume of the excess product, subassembly and component inventories become equal to the truck volume, the truck loaded with excess inventory is sent to a recycling facility. Any product, subassembly or component inventory which is greater than *maximum inventory level* is assumed to be excess. Component volumes are given in Table 2. The volume of an EOL AC is taken as 3 cubic feet. Multi kanban system (MKS) developed by Udomsawat and Gupta [9] is used to control the disassembly line.

Table 1. Precedence relationships among the parts of an AC.

Part Name	Code	Precedence Relationship	Station
Evaporator	A	-	1
Control Box	B	-	2
Blower	C	A,B	3
Air Guide	D	A,B,C	
Motor	E	A,B,C,D	4
Condenser	F	-	5
Fan	G	F	
Protector	H	-	6
Compressor	I	H	

Table 2. Part characteristics.

Part Name	Code	Testing Time		Volume(cft)	Demanded?	Disposal Classification
		Mean	Std. Dev.			
Evaporator	A	-	-	0.181	No	Copper scrap
Control Box	B	5	1	0.083	Yes	Waste
Blower	C	-	-	0.081	No	Waste
Air Guide	D	-	-	0.406	No	Waste
Motor	E	10	2	0.114	Yes	Waste
Condenser	F	-	-	0.327	No	Copper scrap
Fan	G	2	0.2	0.271	Yes	Waste
Protector	H	-	-	0.012	No	Waste
Compressor	I	10	2	0.114	Yes	Waste

3. DESIGN OF EXPERIMENTS STUDY

In this section, we present a comprehensive and quantitative evaluation of the SEPs on the performance of the AC disassembly line by comparing the case with SEPs against the case without SEPs under different experimental conditions. Table 3 presents the factors and factor levels. A full factorial design with 38 factors requires an extensive number of experiments. Therefore, experiments were designed using orthogonal arrays (OAs) which allow for the determination of main effects by making a minimum number of experiments. Specifically, L81 OA was chosen since it requires 81 experiments while accommodating 40 factors with three levels. Discrete event simulation (DES) models of both cases were developed using Arena 11 to determine profit value together with various cost and revenue parameters for each experiment. Each DES experiment was carried out for 60480 minutes, the equivalent of six months with one

eight hour shift per day. The following formula is used in the DES models for the calculation of profit values.

$$Profit = \overbrace{(SR+CR+SCR)}^{\text{Total Revenue}} - \overbrace{(HC+BC+DC+DPC+TC+TPC)}^{\text{Total Cost}} \quad (1)$$

The different cost and revenue components used in Equation (1) can be defined as follows. SR is the total revenue generated by the component sales during the simulated time period (STP). CR is the total revenue generated by the collection of EOL ACs during the STP. SCR is the total revenue generated by selling scrap components during the STP. HC is the total holding cost of components, EOL ACs and subassemblies during the STP. BC is the total backorder cost of components during the STP. DC is the total disassembly cost during the STP. DPC is the total disposal cost of components, EOL ACs and subassemblies during the STP. TC is the total testing cost during the STP. TPC is the total transportation cost during the STP.

In each AC, evaporator and condenser are sold as copper scrap whereas chassis and metal cover are sold as steel scrap. All the other components are regarded as waste components. In order to determine total weight of small components such as screws, cables, total weight of the main components of an AC is multiplied with a *small component weight factor*. In order to calculate the disposal cost of a waste component, the weight is multiplied with the *unit disposal cost*. Disposal cost for subassemblies and products are calculated by multiplying the total weight of waste components in subassembly or product with the *unit disposal cost*. Disposal cost for subassemblies and products are increased by a factor called *disposal cost increase factor for EOL ACs*. Scrap revenue for evaporator and condenser is calculated by multiplying the weight with the *unit copper scrap revenue*. In the calculation of scrap revenue for subassemblies and products, total weight of evaporator and condenser is multiplied with the *unit copper scrap revenue* whereas the total weight of chassis and metal cover is multiplied with the *unit steel scrap revenue*. Scrap revenue for subassemblies and products are decreased by a factor called *scrap revenue decrease factor for EOL ACs*. The total weight of chassis and metal cover is taken as 6 lbs. The time required to retrieve information from the sensors is assumed to be testing time. Duration of this retrieval process is taken as 20 seconds per AC. In the calculation of transportation cost, the operating cost associated with each trip of the truck is assumed to be $50. For each EOL AC, the facility demands a $20 collection fee.

4. RESULTS

Based on the results of DOE studies, various paired-t tests were performed on different performance measures. Table 4 presents the 95% confidence interval, t-value and p-value for each test. According to this table, SEPs achieve statistically significant savings in holding, backorder, disassembly, disposal, testing and transportation costs. Moreover, there are statistically significant improvements in total revenue and profit for the case of SEPs.

Table 3. Factor levels.

No.	Factor	Unit	Levels		
			1	2	3
1	Disposal cost increase factor for EOL ACs	%	5	10	15
2	Scrap revenue decrease factor for EOL ACs	%	5	10	15
3	Mean demand rate for Control Box	parts/hour	10	15	20
4	Mean demand rate for Motor	parts/hour	10	15	20
5	Mean demand rate for Fan	parts/hour	10	15	20
6	Mean demand rate for Compressor	parts/hour	10	15	20
7	Mean arrival rate of EOL ACs	products/hour	10	20	30
8	Mean disassembly time for station 1	minutes	0.75	1	1.25
9	Mean disassembly time for station 2	minutes	0.75	1	1.25
10	Mean disassembly time for station 3	minutes	0.75	1	1.25
11	Mean disassembly time for station 4	minutes	0.50	0.75	1
12	Mean disassembly time for station 5	minutes	0.75	1	1.25
13	Mean disassembly time for station 6	minutes	1	1.5	2
14	Backorder cost rate	%	40	60	80
15	Disassembly cost per minute	$	1	2	3
16	Testing cost per minute	$	0.40	0.50	0.60
17	Holding cost rate	%	10	20	30
18	Weight for Evaporator	lbs.	8	12	16
19	Weight for Motor	lbs.	6	10	14
20	Weight for Condenser	lbs.	12	15	18
21	Weight for Compressor	lbs.	6	10	14
22	Price for Control Box	$	30	60	90
23	Price for Motor	$	50	100	150
24	Price for Fan	$	15	30	45
25	Price for Compressor	$	50	75	100
26	Unit disposal cost	$/lbs	0.30	0.40	0.50
27	Unit copper scrap revenue	$/lbs	0.40	0.60	0.80
28	Unit steel scrap revenue	$/lbs	0.15	0.20	0.25
29	Maximum inventory level	parts, subassemblies, products	5	10	15
30	Small component weight factor	%	5	10	15
31	Probability of a non-functional Control Box	%	10	20	30
32	Probability of a non-functional Motor	%	10	20	30
33	Probability of a non-functional Fan	%	10	20	30
34	Probability of a non-functional Compressor	%	10	20	30
35	Probability of a missing Control Box	%	5	10	15
36	Probability of a missing Motor	%	5	10	15
37	Probability of a missing Fan	%	5	10	15
38	Probability of a missing Compressor	%	5	10	15

5. CONCLUSIONS

Sensors embedded in products can deal with the uncertainty associated with the disassembly yield by providing information on the condition of the components prior to disassembly. In this study, we analyzed the impact of SEPs on the various performance measures of an AC disassembly line. First, two separate DOE studies based on OAs were carried out for the cases with and without

SEPs. Then paired-t tests were performed in order to compare two cases for various performance measures. According to test results, SEPs achieve significant reductions in holding, backorder, disassembly, disposal, testing and transportation costs while increasing total revenue and profit.

Table 4. Paired-t test results for various performance measures.

Performance Measure	95% Confidence Interval on Mean Difference (Sensor –No Sensor)	t-value	p-value
Holding Cost	(-410.850, -95.004)	-3.19	0.002
Backorder Cost	(-64751.7, -47287.2)	-12.77	0.000
Disassembly Cost	(-46141.9, -32744.6)	-11.72	0.000
Disposal Cost	(-34185.6, -22951.7)	-10.12	0.000
Test Cost	(-175859, -150695)	-25.83	0.000
Transportation Cost	(-2223.76, -1708.21)	-15.18	0.000
Total Cost	(-313978, -265077)	-23.56	0.000
Total Revenue	(328616, 448101)	12.94	0.000
Profit	(601697, 754075)	17.71	0.000

REFERENCES

[1] Ilgin, M. A. and Gupta, S. M., "Analysis of a Kanban Controlled Disassembly Line with Sensor Embedded Products," in *Proceedings of the 2009 Northeast Decision Sciences Institute Conference*, Uncasville, Connecticut, 2009, 555-560.

[2] Ilgin, M. A. and Gupta, S. M., "Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art," *Journal of Environmental Management,* 2010, 91, 563-591.

[3] Karlsson, B., "A distributed data processing system for industrial recycling," in *Proceedings of the 1997 IEEE Instrumentation and Measurement Technology Conference*, Ottowa, Canada, 1997, 197-200

[4] Klausner, M., Grimm, W. M., and Hendrickson, C., "Reuse of electric motors in consumer products," *Journal of Industrial Ecology,* 1998, 2, 89-102.

[5] Klausner, M., Grimm, W. M., and Horvath, A., "Integrating product takeback and technical service," in *Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment*, Danvers, MA, 1999, 48-53.

[6] Petriu, E. M., Georganas, N. D., Petriu, D. C., Makrakis, D., and Groza, V. Z., "Sensor-based information appliances," *IEEE Instrumentation & Measurement Magazine,* 2000, 3, 31-35.

[7] Scheidt, L. and Shuqiang, Z., "An approach to achieve reusability of electronic modules," in *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, San Francisco, CA, 1994, 331-336.

[8] Simon, M., Bee, G., Moore, P., Pu, J.-S., and Xie, C., "Modelling of the life cycle of products with data acquisition features," *Computers in Industry,* 2001, 45, 111-122.

[9] Udomsawat, G. and Gupta, S. M., "Multikanban system for disassembly line," in *Environment Conscious Manufacturing*, S. M. Gupta and A. J. D. Lambert, Eds. Boca Raton, FL: CRC Press, 2008, 311-330.

[10] Vadde, S., Kamarthi, S., Gupta, S. M., and Zeid, I., "Product Life Cycle Monitoring via Embedded Sensors," in *Environment Conscious Manufacturing*, S. M. Gupta and A. J. D. Lambert, Eds. Boca Raton, FL: CRC Press, 2008, 91-103.