

Research Publications Related to Environmentally Conscious Manufacturing

1994 – 2002

(Report Prepared: November 2002)

Surendra M. Gupta, Ph.D., PE, Director

Sagar V. Kamarthi, Ph.D., Associate Director



Laboratory for Responsible Manufacturing

Department of MIME, College of Engineering, Northeastern University, Boston, Massachusetts 02115

LRM

Engineering solutions for
evolving customer and
environmental needs

LRM Director's Message



During the last eight years or so, we have made substantial progress here at the Laboratory for Responsible Manufacturing (LRM). Today, in addition to Dr. Kamarthi and myself, our research group consists of a dozen plus research associates working on their Master's, Doctoral and post Doctoral research. The objective of LRM is to develop and assess strategies and methodologies for competitive and agile manufacturing

technologies in response to evolving environmental and customer needs as well as legislative and ethical standards while maintaining profitability.

One of the more important of the many themes of research that are conducted at LRM is in the area of Environmentally Conscious Manufacturing (ECM). ECM is concerned with developing methods for manufacturing new products from conceptual design to final delivery and ultimately to the end-of-life disposal such that all the environmental standards and requirements are satisfied. In the last eight years, we have produced in excess of one hundred documents, representing journal papers, book chapters, papers in conference proceedings and dissertations, in the area of ECM. In addition, the members of LRM have made numerous presentations about their research at International and National Conferences.

This report documents the publications generated in the area of ECM at LRM during the last eight years.

Surendra M. Gupta, Ph.D. PE

Contents

LRM Director's Message	2
Contents	3
Research & Development Capabilities of LRM	4
LRM Directors	8
Publications Related to Environmentally Conscious Manufacturing	11

Research & Development Capabilities of LRM



Laboratory for Responsible Manufacturing (LRM)

Laboratory for Responsible Manufacturing (LRM) in the College of Engineering at Northeastern University is dedicated to conducting basic as well as applied research in manufacturing which covers areas such as Environmentally Conscious Manufacturing, Mass Customization, and Sensor-assisted Monitoring and Diagnosis. The modeling techniques used range from Neural Networks, Multi-agents, Stochastic models, Multi-criteria Optimization, Petri-nets and Graph Theory. The group members have expertise in different areas of research and are capable of working on research and developmental projects in collaboration with the industrial partners and governmental agencies. The following is a compendium of research and development capabilities of the group.

DISASSEMBLY AND RECOVERY OF END OF LIFE PRODUCTS

Industrialized countries all over the world are facing serious aftermath of the rapid development that has taken place in the last few decades. For example, there has been an appalling rate of depletion of natural resources in recent years. This is a direct result of an ever-increasing demand for consumer goods coupled with shortened lifetimes of many products. Although the products are more durable, they are not kept for long because of the rapid change in the state of the art and the consumers' appetite for latest models of products. This phenomenon coupled with serious shortage of landfills and incinerating facilities has led to an environmental threat.

It is widely recognized that the most ecological way to dispose of products at the end of their lives is to reuse, remanufacture or recycle them. In general, it is neither economical nor possible to recycle a product as a whole. Instead, the effort is to maximize the proportion of the product that can be recycled or reused, and minimize ecological devastation by reducing the mass of the product that is sent to the landfills or incinerators. The best way to achieve this is to disassemble the product, so that individual components and materials can be reused or recycled.

Our group has done extensive and seminal work in the area of disassembly scheduling, disassembly process planning, disassembly leveling, cost-benefit analysis of disassembly-related processes and product recovery at the end of life of products. Our experience in these areas puts us at the forefront of disassembly and recovery research.

DESIGN AND MANUFACTURING IN MASS CUSTOMIZATION

As markets reach their saturation limits for many products, and customers grow more demanding, manufacturing industries are forced to enter into the production paradigm of mass customization in which products are designed, manufactured, tested and delivered to satisfy the customers' exclusive requirements. This kind of concentration on the individual customer is taking place in consumer products, automobiles, telecommunications, computer hardware, and a wide range of other products.

We have made good progress into identifying the principles of mass customization and the different factors that influence this customer-oriented business strategy. We have developed a typology of mass-customized production systems and identified different technologies useful for supporting them. We have also been developing functional and

information models of mass-customized production systems to address the issues related to cost implications, operations planning, systems integration, and information management in mass customization environment.

Our work in mass customization helps industrial practitioners in several ways. Our classification of mass-customized production systems assist a company in determining what type of system it should adapt taking into account its existing production capabilities. Using the set of influential factors identified by us, the company can plan, design and implement an appropriate mass-customized production system for the company. We also offer to build intelligent computer tools for operating mass-customized production systems.

PRODUCT REALIZATION FOR RECYCLABILITY AND REUSABILITY

Product designers are usually required to satisfy numerous but often contradicting demands. Those demands not only include designing for appeal or cost efficiency, but also for assembly, manufacturing, and environmentally benign products, also known as the “Design for Environment” (DfE) (or *Green Design*). Conceptually, DfE denotes designing products such that their environmental impact is as small as possible. With proper design, not only can DfE be made more cost efficient, in many cases it could actually generate positive income in the long run. Moreover, it is necessary because of competition, consumer demand and the prevailing laws.

Major manufacturing companies have taken proactive steps towards the greening of products by emphasizing on reducing parts, rationalizing materials, and reusing components. These steps have resulted in savings of millions of dollars per year as reported by many companies.

We have developed various analysis tools to assist and/or evaluate different aspects of product designs. For example, we recently developed a Design for Disassembly Index that enables a designer to measure disassembly and recycling potential of different product designs. The index offers designers with an important measure to help improve future products.

MONITORING AND DIAGNOSTICS OF MANUFACTURING PROCESSES

Manufacturing process monitoring is the activity of identifying characteristic changes of a process without interrupting the normal operation by evaluating the process signatures. Diagnostic activities usually accompany process monitoring. Diagnostics refers to the identification of causes for the change or failure of the process.

This research is concerned with the development of generic methodologies for sensor-assisted intelligent integrated monitoring and diagnostics of manufacturing processes and machine tools. These methodologies emphasize investigating sensor data representation schemes, sensor data fusion techniques, and neural network models, artificial reasoning methods for a variety of industrial applications.

We have developed a methodology for on-line flank wear estimation in turning processes. The results indicate that the methods investigated provide accurate on-line flank wear estimation. Our current plan is to extend the methodology for on-line tool wear estimation in milling and drilling, and in-process workpiece surface roughness assessment in turning, milling, and drilling.

JUST-IN-TIME PRODUCTION AND FLEXIBLE KANBAN SYSTEMS

The Just-In-Time (JIT) philosophy evolved from a number of principles such as the elimination of waste, reduction of production cost, total quality control and recognition of employees' abilities. The objective of JIT is the production of defect free goods in the required amount at the right time. The Kanban system, an element of the JIT system, has many advantages that include ability to control production, simplicity in production scheduling, reduced burden on operators, ease of identification of parts and substantial reduction in paper work.

Since the JIT system was designed for a deterministic environment (e.g., constant processing times and smooth and stable demand), its performance is optimum in that environment. However, once implemented, JIT is fraught with numerous types of uncertainties such as processing time and demand variations, breakdowns and other types of planned or unplanned interruptions.

To address the above-mentioned problems, we have developed a new and systematic design called the Flexible Kanban System (FKS). FKS capitalizes on the strength of JIT and, at the same time, overcomes the problems interjected by uncertainties. We have also focused on implementing JIT in small manufacturing companies which is more challenging because of their susceptibility to fluctuations.

NEURAL NETWORKS AND KNOWLEDGE-BASED SYSTEMS

Neural networks and knowledge-based systems are the intelligent computer tools useful for building powerful decision making systems which can emulate the capabilities of a human expert in a given domain of expertise. In industry, they can be used for several purposes that include interpretation, selection, prediction, monitoring, diagnosis, fault detection, design, planning, control, scheduling, maintenance, etc.

We have developed neural networks and knowledge-based systems for several applications such as form work selection in construction, undergraduate course selection, computer-aided process planning and cost estimation for a sheet metal company, cost reduction in purchasing for the Naval aviation supplies office, and tool wear estimation.

PROCESS MONITORING FOR PRODUCT QUALITY CONTROL

A major goal of process monitoring for product quality control is to detect any special disturbances in the process as early as possible, so that investigation of the process and corrective actions can be taken before many nonconforming products reach the final stage of production. The direct benefits of having a properly designed monitoring system include improved product quality, better plans for maintenance, more effective control of operating machines, and better manufacturing decisions with process and workload plans.

In process monitoring for product quality control, any observed variation in a process variable such as the diameter, length, or surface roughness of a part is attributable to either random causes or assignable causes. From the process control viewpoint, the tendency of any arbitrary pattern to repeat itself should cause concern for investigation into potential assignable causes.

We have developed a general-purpose scheme for process improvement that detects all systematic repetitive patterns from measured data. This new method automatically identifies all repetitive patterns of any structure, even if their length is relatively small.

Once these symptomatic patterns are correctly identified, the results can be used to

identify the underlying reasons and to plan preventive control actions. Some of the numerous possible reasons can be found in voltage fluctuation of a power source, shift changes of operators, unfavorable humidity or temperature changes, and machine tool behavior under different operating conditions. Our pattern recognition-based method is very effective and could lead to an effective process monitoring and diagnosis for quality control.

STOCHASTIC MODELS

Modern manufacturing/ production systems continue to grow in complexity and size. A manufacturing/ production system can be considered as a collection of various service areas where jobs arrive at different rates and demand services with unequal processing times. Due to their non-deterministic behavior, stochastic models are best suited to analyze such systems. The analysis can be performed using either analytical or simulation techniques. Our work has extended the state of the art and developed many analytical techniques to study several types of manufacturing/ production systems. Similarly, we have developed capabilities to use simulation techniques to analyze large and complex systems.

MATERIALS MANAGEMENT

Materials management deals with all aspects of materials passing through a company beginning with the purchase of raw materials to the delivery of finished products. Within the company, it is necessary to determine when and in what quantities to order raw materials from various vendors, produce subassemblies and finished products, and ship finished products to clients. A methodology called the Material Requirements Planning (MRP) does just that. MRP, nonetheless, was designed to operate in a relatively static and predictable environment. However, there are times when these ideal conditions do not mimic the real-life situations.

We have done a lot of work to explore the effect of a variety of probabilistic demands and lead times scenarios on MRP performance. Understanding of such behaviors can lead to the development of strategies to maximize MRP performance in a real-life environment.

DATABASE SYSTEMS FOR PRODUCTION ENVIRONMENT

We can develop high quality customized database systems that can support group technology, design data retrieval, computer-aided process planning, cost optimization and estimation, just-in-time inventory management, etc.

LRM Directors



Director

DR. SURENDRA M. GUPTA

Dr. Surendra M. Gupta is a Professor of Mechanical, Industrial and Manufacturing Engineering and Director of the Laboratory for Responsible Manufacturing at Northeastern University in Boston. He received his BE in Electronics Engineering from Birla Institute of Technology and Science, MBA from Bryant college and MSIE and Ph.D. in Industrial Engineering from Purdue University.

Dr Gupta is a recipient of the Outstanding Research Award and the Outstanding Industrial Engineering Professor Award (in recognition of *Teaching Excellence*). Dr. Gupta's research interests are in the areas of Production/ Manufacturing Systems and Operations Research. He is mostly interested in Environmentally Conscious Manufacturing, Electronics Manufacturing, MRP, JIT, and Queueing Theory. He has authored and co-authored over 200 technical papers published in prestigious journals, books and international conference proceedings. He has traveled widely and presented his work at international conferences on six continents viz., Africa, Asia, Australia, Europe, North America and South America. The journals where his publications have appeared include *Annals of Operations Research*, *Computers and Electrical Engineering*, *Computers and Industrial Engineering*, *Computers and Mathematics with Applications*, *Computers and Operations Research*, *European Journal of Operational Research*, *International Journal of Computer Integrated Manufacturing*, *International Journal of Environmentally Conscious Design and Manufacturing*, *International Journal of Flexible Automation and Integrated Manufacturing*, *International Journal of Industrial Engineering*, *International Journal of Manufacturing Technology and Management*, *International Journal of Operations and Production Management*, *International Journal of Production Economics*, *International Journal of Production Research*, *International Transactions in Operational Research*, *Journal of Electronics Manufacturing*, *Journal of Engineering Sciences*, *Journal of Fire Technology*, *Journal of Industrial Ecology*, *Journal of Intelligent Manufacturing*, *Journal of Operational Research Society*, *Journal of the American Society of Information Science*, *Microelectronics and Reliability*, *Opsearch*, *Perception and Psychophysics*, *Performance Evaluation*, *Performance Evaluation Review*, *Production and Inventory Management Journal*, *Production Planning and Control*, and *Transactions of Operational Research*. His publications have been cited by hundreds of researchers all over the world in journals, proceedings, books, and dissertations.

Dr. Gupta is the editor for the special issues of *Journal of Electronics Manufacturing* on "Environmental, Recycling and End of Life Issues in the Electronics Industry" and "Production, Planning and Scheduling in Electronics Manufacturing", senior editor of the *Industrial Engineering Applications and Practice: Users' Encyclopedia*, co-editor for the special issue of *Computers and Industrial Engineering* on "Operational Issues in Environmentally Conscious Manufacturing" and serves as an Area Editor for Environmental Issues of *Computers and Industrial Engineering* as well as on the editorial boards of *IEEE Transactions on Electronics and the Environment*, *IIE Transactions on Design and Manufacturing*, *International Journal of Industrial Engineering*, *International Journal of Product and Process Development* and *Journal of Electronics Manufacturing*. He has been involved as the Chairman of the *International Conferences on Environmentally Conscious Manufacturing I (Nov. 2000) and II (Oct. 2001)*, track chair of

Management Science and Operations Research for the *NEDSI'2001*, *NEDSI'2002* and *NEDSI'2003* Conferences, and the member of the Technical Committees of International Conferences of *IEEE on ISEE'98*, *ISEE'99*, *ISEE'2000*, *ISEE'2001* and *ISEE'2002*; *DYCONS99*; *GT/CM'2000*; *RETBE'2000*; *ICMFMDI'2000*; *ISLCE'2001*; and *ICRM'2002*. In addition, he is a regular reviewer for more than a dozen major journals in the field of Production/ Manufacturing Systems and Operations Research and has frequently reviewed proposals for National Research Council and National Science Foundation. He has been elected to the memberships of several honor societies and is listed in various Who's Who publications. He is a registered Professional Engineer in the State of Massachusetts and a member of ASEE, DSI, IIE, INFORMS and POMS.

He has taught a variety of undergraduate and graduate courses in the areas of Production/ Manufacturing Systems and Operations Research. He has more than 25 years of teaching experience and has consistently received high student ratings.

He has been elected to memberships and chairmanships of dozens of University, College and Department Committees as well as an elected member of the Faculty Senate representing the College of Engineering.



Associate Director

DR. SAGAR V. KAMARTHI

Dr. Sagar V. Kamarthi is the associate director of the Laboratory for Responsible Manufacturing and is on the faculty of the Department of Mechanical, Industrial and Manufacturing Engineering at Northeastern University, Boston. He received his BS in Chemical Engineering from the Sri Venkateswara University, Tirupati, India, and MS and Ph.D. in Industrial Engineering from the Pennsylvania State University.

His research interests are in the areas of mass customization. The current research plan includes the development of metrics of agility and formulation of principles for mass customization, and creation of intelligent information systems for customer interaction. Since he joined the department four years ago, he has taken the responsibility of teaching both undergraduate and graduate level courses in the area of manufacturing system/engineering and establishing a research focus in the department on agile manufacturing for mass customization. At present he is developing an integrated research, education and industrial partnership plan modeled on the concept of knowledge supply chains. As key a feature of this model, he will use the experience, information and data that result from the industrial partnerships for driving his research and educational activities.

He has been supervising Dr. Stefan Pittner, Postdoctoral Research Associate, for the past four years. At present, he has been advising four doctoral students and three master students on different topics related to his research interests.

He has written several technical papers and been actively seeking collaboration with several industrial partners. The journals where his publications have appeared include *ASME Transactions on Manufacturing Science and Engineering*, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *IIE Transactions*, and *International Journal of Production Research*.

He served as an Associate Editor of the *International Journal of Agile Manufacturing*, Associate Editor of the *Industrial Engineering User's Encyclopedia*, and Editorial Board Member of the *International Journal of Industrial Engineering -- Applications and Practice*.

He is the recipient of several prestigious awards. In 1998 he won the Dell K. Allen Outstanding Young Manufacturing Engineer Award. This award is conferred by the Society of Manufacturing Engineers (SME) and ranks in stature with the SME International Honor Awards and the SME Award of Merit. In 1996 he won the Pritsker Doctoral Dissertation Award given by the Institute of Industrial Engineers (IIE) to the outstanding doctoral dissertation research in the areas related to industrial and manufacturing engineering. In 1989, he won the First Prize in the Fourth Annual Graduate Research Exhibition at the Pennsylvania State University. In 1982 he won the First Prize in the National Student's Design Competition conducted by the Indian Council for Science Museums, Bangalore, India.

He is a member of the SME, ASME, IIE, IEEE, and ASEE. Since 1996, he has been serving Boston IIE Senior Chapter as the Director for NEU Representation.

Publications Related to Environmentally Conscious Manufacturing



1994

- Brennan, L., Gupta, S. M. and Taleb, K., "Operations Planning Issues in an Assembly/Disassembly Environment", *International Journal of Operations and Production Management*, Vol. 14, No. 9, 57-67, 1994.

Abstract— The establishment of disassembly plants and the creation of product designs which specifically facilitate disassembly are enabling manufacturers to carry out item segregation. Item segregation is defined as the separation from an assembly of a part or a group of parts by following a reverse assembly process. Once segregated, the items can be reused, recycled or discarded. However, there are operational problems associated with item segregation. Foremost amongst these are the lack of planning and scheduling mechanisms, difficulty in coping with reverse flow of materials, and item explosion. Despite the economic and environmental benefits of disassembly, researchers and practitioners are lagging behind in developing methodologies to address the operations and production planning and control issues associated with item segregation. This paper is aimed at addressing these issues.

- Gupta, S. M. and Taleb, K., "Scheduling Disassembly", *International Journal of Production Research*, Vol. 32, No. 8, 1857-1866, 1994.

Abstract— We present an algorithm for scheduling the disassembly of discrete parts products characterized by a well defined product structure. As opposed to MRP where the demand occurs at the end item level, the demand in the disassembly case is motivated by the component level of the product structure. Even though the objective in the disassembly case is the reverse of that of MRP, the algorithm itself is not the reverse of the MRP algorithm. It is considerably more complicated. An example is presented and its implementation in a spreadsheet is described.



1995

- Taleb, K. and Gupta, S. M., "Algorithms for Disassembly", *Proceedings of the 1995 Northeast Decision Sciences Institute Conference*, Providence, Rhode Island, 406-408, March 22-24, 1995.

Abstract— This paper presents the basic structure for two disassembly scheduling algorithms applied to a single product structure. The first algorithm addresses the case when all items in the product structure are unique, The second algorithm accounts for common items.

- Taleb, K., "Disassembly Scheduling", *PhD Thesis*, (Advisor: Dr. S. M. Gupta), Department of Industrial Engineering and Information Systems, Northeastern University, June 1995.

Abstract— Disassembly and materials recovery is currently a growing trend in industrialized nations. It is a natural result of today's fundamental changes in economics, the alarming depletion of

natural resources, and the powerful environmental movements. A few governments have already passed regulations that force manufacturers to take back and dismantle their used products so that components and materials can be reused and/or recycled. In addition to this new trend of disassembly, the manufacturing sector also has been experiencing other important trends such as components and materials commonality. All these trends and recent changes have led to this effort.

We principally address the operational and planning aspects of the material requirements for disassembly operations. Materials Requirements Planning (MRP) is a widely used procedure for production planning, but it is assembly oriented and cannot be used for the planning of disassembly operations. Perhaps the single most important difference between assembly and disassembly settings is the number of demand sources. In an assembly setting, the parts tend to converge to a single demand source and they are moving on the manufacturing floor. This single demand source is the final product, and the material management's governing principles are constrained by this "convergence" property. Under a disassembly setting, as the parts start moving away from their source of origin, they tend to diverge from each other and lead to a "divergence" property.

This thesis can be divided into two parts. The objective of the first part is to identify and analyze technical and operational challenges facing disassembly and their transitional and long-term impact on the manufacturing sector. The second part lays the foundation for a complete disassembly scheduling system of the future. To this end, three heuristic algorithms have been developed. These algorithms can be used to find a disassembly schedule for the root(s) and subassemblies when the demand occurs at the component level of the product structure. The three algorithms deal respectively with a single product structure with no commonality, a single product structure with commonality, and multiple product structures with commonality. The problems that these algorithms address are non polynomial (NP), yet the complexity of the algorithms presented is of the order of $O(n)$ where n is the number of root items. Thus, the algorithms are very efficient. The results obtained by using these algorithms were either optimal or very close to optimal.



1996

- Gupta, S. M. and McLean C. R., "Disassembly of Products", ***Computers and Industrial Engineering***, Vol. 31, 225-228, 1996.

Abstract— With incoming recycling regulations, resource conservation needs and an increased awareness of the state of the environment by both the consumer and the producer, a fundamental reappraisal of the traditional manufacturing paradigm has been emerging. The manufacturers are under tremendous pressure to dispose of products in an environmentally responsible manner. To this end many companies are establishing disassembly plants and developing product designs which specifically facilitate disassembly. Once disassembled, the items can be reused, recycled or discarded. This paper provides an overview of the research in the area of disassembly of products.

- Gupta, S. M. and Taleb, K., "An Algorithm to Disassemble Multiple Product Structures with Multiple Occurrence of Parts", ***Proceedings of the International Seminar on Reuse***, Eindhoven, The Netherlands, 153-162, November 11-13, 1996.

Abstract— In this paper, we present an algorithm to obtain a disassembling scheme for the complex problem involving multiple product structures where the parts/materials have multiple occurrences. In particular, the algorithm determines the quantity and operations schedule of disassembly for all product structures (including the ordering of the roots and the disassembly schedule for the roots and the subassemblies) in order to fulfill the demand for the various parts. An overview of the

algorithm is presented together with the results of an example to illustrate the workings of the algorithm.

- Gupta, S. M., and Veerakamolmal, P., "Disassembly of Products", ***NIST Systems Integration for Manufacturing Application Program Grant No.***, 60NANB5D0112 Final Report, December 1996.

Abstract— The outline of this report consists of Introduction, Literature Review, Material Recovery Systems, Disassembly Process Planning, A Decision Tool to Assess the Impact of Automobile Design on Disposal Strategies, Summary and Future Research.

- Isaacs, J. A., Gupta, S. M. and Messac, A., "A Decision Tool to Assess the Impact of Automobile Design on Disposal Strategies", ***Proceedings of the Environmentally Conscious Manufacturing and Design Conference***, Cleveland, Ohio, 207-214, July 23-25, 1996.

Abstract— With the increasing use of lighter materials to enhance fuel economy, the steel-dominated materials content in automobiles is changing to include a greater fraction of polymers and aluminum. This change may substantially impact the end-of-life (EOL) automobile disposal process. In light of impending regulations, various alternatives for component and material disposal are under investigation. Tradeoffs between technological and economic feasibility and the degree of environmental detriment must be optimized. This paper presents a preliminary application of a newly developed decision tool, called physical programming, to assess the alternative EOL disposal strategies of future vehicles. Physical programming addresses problems involving multiple objectives and constraints and allows the decision maker to express his/her value-system in a realistic manner for each objective of interest.

- Moyer, L., "Assembly and Disassembly Models in Electronics Manufacturing", ***PhD Thesis***, (Advisor: Dr. S. M. Gupta), Department of Mechanical, Industrial and Manufacturing Engineering, Northeastern University, September 1996.

Abstract— Surface Mount Technology (SMT) is a popular method of Printed Circuit Board (PCB) assembly in which high speed automated assembly machines are capable of placing in excess of 40,000 components per hour. In order to achieve these impressive assembly rates, complex placement machines must be programmed efficiently.

The complexity of a printed circuit board assembly process is highly dependent on the level of automation, type of placement or insertion system, and the characteristics of the board under production. In this thesis, an analysis of an automated surface mount process, with primary concentration on the High Speed Chip Shooter (HSCS) machine, is presented. Modeling the system, developing the problem formulation, and establishing alternative assembly methodologies that are capable of improving the existing surface mount process are the primary objectives of this work.

The HSCS machine consists of a feeder mechanism, pick and place mechanism, and a positioning table. One of the main planning difficulties with this type of system is establishing effective and efficient movement between the three concurrent mechanisms. Operations research principles and procedures are utilized in the development of the problem formulation and heuristic development with respect to the component placement sequence, the coordination of the mechanisms involved, and the minimization of the total system time per board.

Determining the component placement sequence, also referred to as the placement path, is an NP-complete problem that best resembles the Traveling Salesman Problem, while another problem posed by the coordination of the mechanisms closely resembles the Quadratic Assignment Problem. In this thesis, several heuristic algorithms are developed and tested against previously published subproblems, and applied to a real-life working board configuration.

Finally, the effect of electronics assembly, disassembly, and disposal on the environment is reviewed and the potential hazards of continuing the present trends in electronics parts disposal is discussed. This discussion emphasizes the growing size of this problem in a world of increasing technology, where electronic products dominate. In order to promote and support this new environmental ethic in electronics assembly and disassembly, the need for improved methods of electronics reuse, minimization of life-cycle scrap, development of planning tools, and an increase in research activity in this area is also highlighted.

- Zeid, I., Gupta, S. M. and Bardasz, T., "An Analogical Problem Solving Approach to Planning for Disassembly", ***Proceedings of the Winter Annual Meeting of ASME (Design for Manufacturing and Assembly, DE-Vol. 89)***, Atlanta, Georgia, 79-89, November 17-22, 1996

Abstract— Disassembly has been emerging as an important potential response to recent environmental and recycling regulations as well as resource conservation needs. One can identify two distinct approaches to tackle the disassembly problem, viz., design for disassembly (DFD) and planning for disassembly (PFD). This paper focuses on the PFD approach. The evolution of a disassembly plan may require some heuristics and domain specific knowledge. In addition, disassembly planners may have a particular style to solve disassembly problems. Due to these facts and the nature of the PFD itself (open ended and iterative), the paper proposes the use of Analogical Problem Solving (APS) as an approach to assist planners to solve PFD problems. APS is based on the sensible notion that problem solving can be assisted by the reuse of solutions to similar problems encountered in the past. The framework of applying APS to PFD, the merits of this approach, and the issues relating to its use for PFD are discussed.

1997

- Gungor, A. and Gupta, S. M., "An Evaluation Methodology for disassembly Processes", ***Computers and Industrial Engineering***, Vol. 33, No. 1, 329-332, 1997.

Abstract— Disassembly is a systematic process that allows reusable, non-recyclable, and hazardous subassemblies to be selectively separated from recyclable ones. In this paper, we present a methodology to evaluate different disassembly strategies so that the best one could be chosen. Since the identification of all possible disassembly sequences of complex products is not an easy task, we also propose a disassembly sequence generation heuristic which gives a near optimum disassembly sequence for a product. The application of the methodology is illustrated by considering an IBM PS/2 Model 30 computer base.

- Gupta, S. M. and Isaacs, J. A., "Value Analysis of Disposal Strategies for Automobiles", ***Computers and Industrial Engineering***, Vol. 33, No. 1, 325-328, 1997.

Abstract— Alternative disposal strategies for vehicle design with varying relative proportions of materials, are explored using goal programming to analyze the tradeoffs between technological, economic, and environment factors. Two vehicle designs - one based on a steel unibody and the other more intensively designed with polymer materials - were selected for investigation. The preliminary results indicate that if properly controlled, the current automobile recycling infrastructure in the U.S. can remain economically viable while improving with respect to environmental considerations.

- Isaacs, J. A. and Gupta, S. M., "Economic Consequences of Increasing Polymer Content on the U. S. Automobile Recycling Infrastructure", ***Journal of Industrial Ecology***, Vol. 1, No. 4, 19-33, 1997.

Abstract— Environmental awareness regarding resource use and emissions over the life cycle of the automobile has heightened the concerns for end-of-life (EOL) vehicle disposal. With increasing use of lighter materials to enhance fuel economy, the steel-dominated content of automobiles is changing to include a greater fraction of polymers. This change may substantially impact vehicle disposal. In light of impending regulations, various alternatives for remanufacturing and reuse of components and material disposal are under investigation. For example, if shredder operations are used to reclaim metallic materials, then the extent of disassembly will significantly impact profitability as well as the environment. Therefore tradeoffs between technological and economic feasibility, and the degree of environmental detriment must be identified for disposal scenarios of interest. Using goal programming, changes to the current US vehicle recycling infrastructure are explored for their effects on dismantler and shredder profitabilities. To investigate the effect of lightweighting on the profitability of the recycling infrastructure, two specific vehicle designs are compared: a steel unibody and a polymer intensive vehicle. Other scenarios examine the outcomes for mandating removal of polymer materials during disassembly, and for increasing the disposal cost of scrap polymer to that of hazardous waste. Goal programming addresses multi-objective problems involving linear multiple criteria and linear constraints, and allows the exploration of the vehicle recycling infrastructure profitability for prescribed target profits under varying conditions. These results indicate that if properly controlled, the current automobile recycling infrastructure in the US can remain economically viable while improving with respect to environmental considerations. Alternatively, implementation of certain policies that reduce profitability could cause disastrous consequences, resulting in the economic collapse of the infrastructure.

- Isaacs, J. A. and Gupta, S. M., "Effect of Vehicle Lightweighting on the Profitability of the Automobile Recycling Infrastructure", ***Proceedings of The Julian Szekely Memorial Symposium on Materials Processing***, Edited by H.Y.Sohn, J.W.Evans, and D. Apelian, The Minerals, Metals & Materials Society, Cambridge, Massachusetts, 669-685, October 5-8, 1997.

Abstract— Environmental awareness regarding resource use and emissions over the life cycle of the automobile has recently grown and has heightened concerns for end-of-life (EOL) vehicle disposal. With increasing use of lighter materials to enhance fuel economy, the steel dominated materials content in vehicles is changing to include greater fractions of polymers and aluminum. This change may substantially impact vehicle disposal. In light of impending regulations, various alternatives for remanufacturing and reuse of components and material disposal are under investigation. For example, if shredder operations are used for reclaiming metallic materials for disposal, then the extent of disassembly significantly impacts the process profitability as well as the environment. Tradeoffs among technological and economic feasibility, and the degree of environmental detriment must be determined for each alternative. Using goal programming techniques and a model of the automobile recycling infrastructure, materials streams and process profitabilities are tracked for different processing scenarios. Optimal quantities of disassembled

materials prior to shredding are determined which would maintain a preferred level of profitability for both the disassembler and the shredder. The three vehicle designs are considered which focus on materials in a specific class, i.e., plain carbon steels in a standard unibody vehicle, polymer composites based on body panel substitution in a unibody and aluminum alloys based on a space frame design. For each of these vehicle designs, the system model is used to generate information regarding the profitability of the recycling infrastructure. The steel unibody design is used as a base case to simulate current recycling infrastructure conditions. Various scenarios are then run to demonstrate the consequences for disassembler and shredder profitabilities with changes in: i) decreasing the ferrous content in the vehicle design, ii) increasing the quantity of polymer materials removed from the EOL vehicle during disassembly, and iii) increasing disposal costs for automobile shredder residue. The results indicate that the current automobile recycling infrastructure in the U.S. can remain economically viable while improving with respect to environmental considerations.

- Moyer, L. and Gupta, S. M., "Environmental Concerns and Recycling/ Disassembly Efforts in the Electronics Industry", *Journal of Electronics Manufacturing*, Vol. 7, No. 1, 1-22, 1997.

Abstract— This paper reviews the problems that many electronics manufacturers are facing in a society of rules and regulations that are becoming increasingly environmentally conscious. The effect of electronics assembly, disassembly, and disposal on the environment is reviewed and the potential hazards of continuing the present trends in electronics parts disposal is discussed. The paper contains a comprehensive survey of previous work related to environmentally conscious manufacturing practices, recycling, and the complexities of disassembly in the electronics industry. Interest in this area has intensified in the recent years due to an increased awareness of the problem in a world of high technology, where electronic products dominate. Industrial applications of recycling programs are presented and existing methodologies and evaluation systems are discussed. In order to promote and support this new environmental ethic in electronics assembly and disassembly, the need for improved methods of electronics reuse, minimization of life-cycle scrap, development of planning tools, and an increase in research activity in this area is also highlighted.

- Taleb, K. and Gupta, S. M., "Disassembly of Multiple Product Structures", *Computers and Industrial Engineering*, Vol. 32, No. 4, 949-961, 1997.

Abstract— In this paper, we address the problem of scheduling the disassembly of discrete parts products characterized by well defined product structures. We allow for the existence of multiple product structures as well as the existence of common parts and/or materials which makes the problem very complex. To this end, we present two companion algorithms which can be applied to obtain a disassembling scheme for such problems. Specifically, the algorithms determine the quantity and operations schedule of disassembly for all product structures (including the ordering of the roots and the disassembly schedule for the roots and the subassemblies) in order to fulfill the demand for the various parts. An example is presented to illustrate the use of the algorithms.

- Taleb, K., Gupta, S. M. and Brennan, L., "Disassembly of Complex Products with Parts and Materials Commonality", *Production Planning and Control*, Vol. 8, No. 3, 255-269, 1997.

Abstract— This paper addresses the issue of parts and materials commonality when scheduling disassembly. In a disassembly environment, inventory management is complex due to the presence of multiple demand sources at the component level of the product structure. Commonality introduces a new layer of complexity by creating alternative procurement sources for the common component items. A novel scheduling algorithm is presented, followed by an example.

- Veerakamolmal, P., Gupta, S. M. and McLean C. R., "Disassembly Process Planning", ***Proceedings of the First International Conference on Engineering Design and Automation***, Bangkok, Thailand, 162-165, March 18-21, 1997.

Abstract— The majority of modern day products contain thousands of parts and many different technologies. Many parts are reusable and some even possess a higher reliability rating than their new counterparts. In order to maintain the integrity of reusable parts, disassembly process planning has to make sure that the identified parts are retrieved properly. Planning for a disassembly process, as the number of parts increases, becomes more and more complex. In a product with 10 parts, there are potentially 10! (3,628,800) possible disassembly sequences. Thus, proper planning is necessary in order to identify the best plan. This research proposes a methodology to generate a disassembly process plan according to the product's modularity.

- Zeid, I., Gupta, S. M. and Bardasz, T., "A Case-Based Reasoning Approach to Planning for Disassembly", ***Journal of Intelligent Manufacturing***, Vol. 8, No. 2, 97-106, 1997.

Abstract— With recycling regulations, resource conservation needs and an increased awareness of the state of the environment by both the consumer and the producer, many companies are establishing disassembly plants and developing product designs which specifically facilitate disassembly. Once disassembled, the items can be reused, recycled or discarded. One can identify two distinct aspects of the disassembly problem, viz., design for disassembly (DFD) and planning for disassembly (PFD). The goal of DFD is to design products that are easy to disassemble. On the other hand, the objective of PFD is to identify efficient sequences to disassemble products. This paper focuses on the PFD aspect of disassembly. Due to the fact that there could be many ways to disassemble a given product, the PFD knowledge is accumulated by experience. Such knowledge is valuable and should be captured, saved and re-used to solve similar problems that arise in the future. In this paper, we propose Case-Based Reasoning (CBR), as an approach, to solve PFD problems. CBR is based on the fundamental principle that problem solving can benefit from solutions to past problems that have been attempted. The technique and issues related to the application of CBR to PFD are presented.

1998

- Gungor, A. and Gupta, S. M., "Disassembly Sequence Planning for Complete Disassembly in Product Recovery", ***Proceedings of the 1998 Northeast Decision Sciences Institute Conference***, Boston, Massachusetts, 250-252, March 25-27, 1998.

Abstract— Disassembly is a key element for retrieving the desired subassemblies and/or parts from a product. However, determining an efficient disassembly sequence plan (DSP) is an NP-complete problem. In this paper, we propose a methodology to generate a near optimum DSP for a product. The methodology is illustrated using an example.

- Gungor, A. and Gupta, S. M., "Disassembly Sequence Planning for Products with Defective Parts in Product Recovery", ***Computers and Industrial Engineering***, Vol. 35, No. 1-2, 161-164, 1998.

Abstract— Recycling and remanufacturing are important forms of product/material recovery which involve product disassembly to retrieve the desired parts and/or subassemblies. Disassembly is a systematic method for separating a product into its constituent parts, components or other groupings. Efficient disassembly requires development of disassembly sequence plans (DSPs). Generating DSPs describing the sequence of parts during disassembly is not a trivial problem since DSP generation is described to be NP-complete. Further complicating matters is the presence of a high degree of uncertainty due to upgrading/downgrading of the product during its use by the customers and defects occurring either when in use or during disassembly. In this paper, we address the uncertainty related difficulties in disassembly sequence planning. To this end, we present a methodology to develop a framework for dealing with uncertainty in DSP implementation and demonstrate it using a simple example.

- Gupta, S. M. and Veerakamolmal, P., "Profitability Measure for Product Disassembly and Recycling ", ***Proceedings of the 1998 POMS-Cape Town Meeting***, Cape Town, South Africa, June 29-July 2, pp. 139-147, 1998.

Abstract— In recent years there has been an appalling rate of depletion of natural resources due to an ever-increasing number of consumer goods manufactured, in turn leading to an increase in the quantity of used and outdated products discarded. From an environmental point of view, it is not only desirable to disassemble, reuse and/or recycle the materials and components from the discarded products, it can also be economically justified. This paper presents a quantitative methodology to measure the profitability for product disassembly and recycling by taking both operational and environmental factors into account. To this end, a two-stage solution model that provides a unique solution for planning component recovery from products with component commonality is presented. The objective of the component recovery model is to compute the number of products to disassemble, in order to fulfill the demand of the components, at the minimal disassembly and disposal costs. An example is presented to illustrate the methodology.

- Kizilkaya, E. and Gupta, S. M., "Material Flow Control and Scheduling in a Disassembly Environment", ***Computers and Industrial Engineering***, Vol. 35, No. 1-2, 93-96, 1998.

Abstract— This paper presents a technique to control the material flow in a disassembly environment using the Flexible Kanban System (FKS). The implementation and effectiveness of the FKS is demonstrated using a case example.

- Kizilkaya, P. and Gupta, S. M., "Use of Flexible Kanban for Material Flow control in a Disassembly Process", ***Proceedings of the 1998 Northeast Decision Sciences Institute Conference***, Boston, Massachusetts, 293-295, March 25-27, 1998.

Abstract— Disassembly is one of the proposed solutions to today's increased environmental problem of large-scale disposal of manufactured products. Disassembly process brings with it a lot of unresolved material control issues. In this paper we illustrate the implementation of the recently developed Flexible Kanban System to cope with the uncertainties that are unique to the disassembly system.

- Korugan, A. and Gupta, S. M., "A Multi-Echelon Inventory System with Returns", ***Computers and Industrial Engineering***, Vol. 35, No. 1-2, 145-148, 1998.

Abstract— This paper considers a two-echelon inventory system with return flows, where demand and return rates are mutually independent. An open queueing network with finite buffers is used to model the system. The model is analyzed using the expansion methodology.

- Moore, K. E., "Petri Nets for Disassembly Process Planning and Performance Modeling of Flexible Kanban System", *PhD Thesis*, (Advisor: Dr. S. M. Gupta), Department of Mechanical, Industrial and Manufacturing Engineering, Northeastern University, September 1998.

Abstract— The objective of this research is to develop Petri net (PN) models and modeling techniques, which provide both quantitative and qualitative modeling capabilities and which can be applied to systems of arbitrary size.

In this research, we develop algorithms to automatically generate a disassembly PN (DPN) from a geometrically based disassembly precedence matrix. The first of these, the DPN-CAO algorithm, generates a DPN for products with complex AND/OR disassembly precedence relationships. The second, the DPN-XOR algorithm, generates a DPN for products with XOR disassembly precedence relationships. We show that the resulting DPNs are live, bounded, and reversible. The resulting DPNs can be analyzed to identify the optimal disassembly process plan (DPP) using the reachability tree method; however, this method is exhaustive. As a result, we develop a heuristic algorithm which uses product information (disassembly times, directions, and tools) and disassembly priorities (e.g., early removal of hazardous components) to generate an optimal or near-optimal DPP.

To our knowledge, these are the first algorithms to automatically generate DPNs for products with complex AND/OR and XOR precedence relationships. Further, we show that the resulting DPNs are live, bounded, and reversible. These algorithms can be used to handle products that are more complex than any that have appeared in the disassembly process planning literature, and have strong potential for industrial applications.

- Moore, K. E., Gungor, A. and Gupta, S. M., "A Petri Net Approach to Disassembly Process Planning", *Computers and Industrial Engineering*, Vol. 35, No. 1-2, 165-168, 1998.

Abstract— Recycling and remanufacturing involve product disassembly to retrieve the desired parts and/or subassemblies. Disassembly is a systematic method for separating a product into its constituent parts, components, or other groupings. Disassembly process planning is critical in minimizing the amount of resources (e.g., time and money) invested in disassembly and maximizing the level of automation of the disassembly process and the quality of the parts (or materials) recovered. We propose an algorithm which automatically generates a disassembly Petri net (DPN) from a geometrically-based precedence matrix. The resulting DPN can be analyzed to generate all feasible disassembly process plans (DPPs), and cost functions can be used to determine the optimal DPP; alternatively, heuristic methods may be used to generate near-optimal DPPs.

- Moore, K. E., Gungor, A. and Gupta, S. M., "Disassembly Petri Net Generation in the Presence of XOR Precedence Relationships", *Proceedings of the 1998 IEEE International Conference on Systems, Man and Cybernetics*, La Jolla, California, October 11-14, pp. 13-18, 1998.

Abstract— A disassembly process plan (DPP) is a sequence of disassembly tasks which begins with a product to be disassembled and terminates in a state where all the parts of interest are disconnected. Disassembly process planning is critical for minimizing the resources invested in

disassembly and maximizing the level of automation of the disassembly process and the quality of the parts (or materials) recovered. In this paper, we propose an algorithm which automatically generates a disassembly PN (DPN) from a geometrically-based disassembly precedence matrix (DPM). This algorithm can be used to generate DPPs for products which contain simple AND, OR, complex AND/OR, and XOR relationships. The resulting DPN can be analyzed using the reachability tree method to generate all feasible disassembly process plans (DPPs), and cost functions can be used to determine the optimal DPP. An example is used to illustrate the procedure.

- Moore, K. E., Gungor, A. and Gupta, S. M., "Disassembly Process Planning using Petri Nets", *Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment*, Oak Brook, Illinois, May 4-6, pp. 88-93, 1998.

Abstract— We generate a disassembly PN (DPN) from a disassembly precedence matrix. The resulting DPN can be analyzed using the reachability tree method to generate all feasible disassembly process plans (DPPs), and cost functions can be used to determine the optimal DPP. Since generating the reachability tree is NP-complete, we develop a heuristic algorithm to limit the size of the reachability tree. The algorithm employs multi-hypothesis search to dynamically explore the v likeliest lowest cost branches of the tree, in order to identify near-optimal DPPs. The cost function incorporates tool changes, changes in direction movement, and individual part characteristics (e.g., hazardous). An example is used to illustrate the procedure.

- Veerakamolmal, P. and Gupta, S. M., "Optimal Analysis of Lot Size Balancing for Multi-Products Selective Disassembly", *International Journal of Flexible Automation and Integrated Manufacturing*, Vol. 6. No. 3/4, 245-269, 1998.

Abstract— In recent years there has been an appalling rate of depletion of natural resources due to an ever-increasing number of consumer goods manufactured, in turn leading to an increase in the quantity of used and outdated products discarded. From an environmental point of view, it is not only desirable to disassemble, reuse and/or recycle the components and materials from the discarded products, in many cases it can also be economically justified. This paper presents a quantitative methodology for product disassembly and recycling by taking both operational and environmental factors into account. To this end, a mathematical programming model that provides a unique solution for planning component recovery from products with component commonality is presented. The objective of the component recovery model is to compute the number of products to disassemble, in order to fulfill the demand of the components, at the minimal disassembly and disposal costs. A case study is presented to illustrate the methodology.

- Veerakamolmal, P. and Gupta, S. M., "Design of an Integrated Component Recovery System", *Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment*, Oak Brook, Illinois, May 4-6, pp. 264-269, 1998.


Abstract— This paper presents a two-stage disassembly and retrieval system that provides a unique solution for planning selective component recovery from products. The solution approach uses process sequencing technique to schedule the operations in both stages to optimize the operational makespan.

- Veerakamolmal, P. and Gupta, S. M., “High-Mix/Low-Volume Batch of Electronic Equipment Disassembly”, ***Computers and Industrial Engineering***, Vol. 35, No. 1-2, 65-68, 1998.

Abstract— This paper presents a procedure to disassemble electronic products with multiple subassembly modules. First, a partial schedule for each subassembly is obtained. The next step modifies the partial schedule in order to minimize the machine idle time at the retrieval process and, thus, the resulting makespan of the whole process. The procedure offers an optimal process makespan according to the sequence in which the batch of products pass through the disassembly and recovery processes. Special emphasis is placed on applying variant process planning methodology for disassembly and retrieval.

- Veerakamolmal, P. and Gupta, S. M., “Planning Components Recovery from Multiple Products”, ***Proceedings of the 1998 Northeast Decision Sciences Institute Conference***, Boston, Massachusetts, 270-272, March 25-27, 1998.

Abstract— This paper presents a two-stage model that provides a unique solution for planning components recovery from products with components commonality. The objective of the model is to determine the number and type of products to disassemble, to fulfill the demand of various components, in order to minimize disassembly and disposal costs.

 **1999**

- Aksoy, H. K. and Gupta, S. M., “An Analytical Model for Remanufacturing Systems”, ***Proceedings of the 1999 Annual Meeting of the Northeast Decision Sciences Institute***, Newport, Rhode Island, March 24-26, pp. 83-85, 1999.

Abstract— In this paper, we introduce an open queueing network with finite buffers to model a remanufacturing system. The system consists of three modules, viz., a testing module for returned products, a disposition module for non-reusable returns and a remanufacturing module. We analyze the network using the decomposition principle and the expansion methodology. The model has been shown to be very rigorous and remarkably accurate. An example is presented to illustrate the use of the model.

- Aksoy, H. K. and Gupta, S. M., “An Open Queueing Network Model for Remanufacturing Systems”, ***Proceedings of the 25th International Conference on Computers and Industrial Engineering***, New Orleans, Louisiana, March 29-April 1, pp. 62-65, 1999.

Abstract— In this paper, we develop an open queueing network model to obtain the total cost performance of a remanufacturing system. The model is developed using decomposition, isolation and expansion methodologies. The remanufacturing system consists of three modules, viz., a disassembly and testing module for returned products, a disposition module for non-reusable returns and a remanufacturing module. The model is thoroughly tested using an experimental design based on orthogonal arrays. The results show that the model is very robust and remarkably accurate.

- Boon, J., Gupta, S. M. and Isaacs, J., “Economic Modeling of Electric Vehicle Battery Recycling”, ***Proceedings of the International Symposium on Manufacturing and Robotics***, Ottawa, Canada, August 5-7, 1999.

Abstract— Electric vehicles (EVs) are being driven throughout the U.S. When these vehicles reach the end-of-life (EOL), their use of lighter materials such as aluminum and composites and the presence of a battery pack may impact vehicle recycling. Using goal programming techniques and a model of the automobile recycling infrastructure, materials streams and process profitabilities are tracked for General Motors' EV, the EV1. The significant amount of aluminum found in the EV1 will make it very profitable to shred as long as waste disposal costs remain low. However, there is considerable uncertainty regarding the profits that the disassembler will achieve. Although under typical market conditions, the lead acid battery pack will generate significant revenue for the disassembler and battery recycler, the immature and possibly limited market for used EV parts may result in reduced profits for the disassembler. Even so, the results indicate that the current automobile recycling infrastructure in the U.S. will be viable for recycling EVs.

- Guide Jr., V. D. R. and Gupta, S. M., “A Queueing Network Model for Remanufacturing Production Systems”, ***Proceedings of the Second International Seminar on Reuse***, Eindhoven, The Netherlands, March 1-3, pp. 115-128, 1999.

Abstract— Developing models to study remanufacturing production processes is a difficult task due to the complexity of remanufacturing systems. A typical remanufacturing system consists of disassembly, remanufacturing, and reassembly operations. Previous models have been limited to simulation studies that require extensive time to develop, execute, and analyze. Given the complexity of most simulation models, it may be difficult to isolate specific cause-and-effect relationships required to develop effective manufacturing control techniques. We develop a queueing network model for a remanufacturing production system and present approximate solutions. A decomposition approach is used where the remanufacturing production process is decomposed into: a disassembly segment, a remanufacturing operations segment, and a reassembly segment. The disassembly segment is modeled as a simple queue, the remanufacturing segment is modeled as an open Jackson network, and the reassembly segment as a kitting process. The queueing model is compared with a simulation network model and error bounds are set. The advantages of an analytic model are discussed and applications are presented.

- Gungor, A. and Gupta, S. M., “A Systematic Solution Approach to the Disassembly Line Balancing Problem”, ***Proceedings of the 25th International Conference on Computers and Industrial Engineering***, New Orleans, Louisiana, March 29-April 1, pp. 70-73, 1999.

Abstract— Disassembly is a systematic method for separating a product into its constituent parts, materials, or other groupings. While disassembly process planning is critical in minimizing the amount of resources (e.g., time and money) invested in the disassembly process, solving the disassembly line balancing problem (DLBP) is crucial to maximizing the utilization of the line on which the products are taken apart. We propose a systematic approach for solving the DLBP by considering several important factors unique to disassembly when balancing the disassembly line. An example is given to illustrate the approach.

- Gungor, A. and Gupta, S. M., “Disassembly Line Balancing”, ***Proceedings of the 1999 Annual Meeting of the Northeast Decision Sciences Institute***, Newport, Rhode Island, March 24-26, pp. 193-195, 1999.

Abstract— In this paper, we discuss a new problem, the disassembly line balancing problem (DLBP), which can simply be defined as the optimum assignment of disassembly tasks to the disassembly workstations under the condition that the precedence relationships among the tasks are not violated. The objectives are to meet the demand and to utilize the disassembly line as efficiently as possible. We present a systematic approach to solve a simple DLBP. An example is also presented to illustrate the approach.

- Gungor, A. and Gupta, S. M., "Issues in Environmentally Conscious Manufacturing and Product Recovery: A Survey", *Computers and Industrial Engineering*, Vol. 36, No. 4, 811-853, 1999.

Abstract— Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) has become an obligation to the environment and to the society itself, enforced primarily by governmental regulations and customer perspective on environmental issues. This is mainly driven by the escalating deterioration of the environment, e.g., diminishing raw material resources, overflowing waste sites, and increasing levels of pollution. ECMPRO involves integrating environmental thinking into new product development including design, material selection, manufacturing processes and delivery of the product to the consumers, plus the end-of-life management of the product after its useful life. ECMPRO related issues have found a large following in industry and academia who aim to find solutions to the problems that arise in this newly emerged research area. Problems are widespread including the ones related to life cycle of products, disassembly, material recovery, remanufacturing, and pollution prevention. In this paper, we present the development of research in ECMPRO and provide a state-of-the-art survey of published work.

- Gungor, A., "Algorithmic Models for Analysis of Disassembly Processes and Systems", *PhD Thesis*, (Advisor: Dr. S. M. Gupta), Department of Mechanical, Industrial and Manufacturing Engineering, Northeastern University, September 1999.

Abstract— There has been an increasing trend toward environmentally conscious manufacturing and product recovery (ECMPRO) among manufacturers around the world; this trend has developed in response to both regulatory (government) and consumer pressures. ECMPRO involves the entire life cycle of products, from conceptual design to final delivery, and ultimately to the end-of-life (EOL) disposal of the products, such that the environmental standards and requirements are satisfied. A major element of EOL processing is product recovery which includes recycling and remanufacturing. Both recycling and remanufacturing involve product disassembly in order to retrieve the desired parts and/or subassemblies. The vast majority of current disassembly activities are manual, entailing high labor costs, particularly in the presence of hazardous materials. In order to reduce the cost of disassembly process in the overall scheme of product recovery, it must be planned and executed efficiently.

Goals related to the disassembly of EOL products include determining the disassembly sequences and improving the systems where the process of disassembly is carried out. Identifying the important issues in disassembly, modeling their effects on disassembly and ultimately on product recovery and providing solution approaches that are capable of improving the existing disassembly systems are the primary objectives of this work.

First, an extensive literature review on ECMPRO is provided to develop a background on the environmental degradation and the development of environmentally friendly practices. Next, an algorithm is presented to identify a geometrically-based disassembly precedence matrix (DPM) from a CAD drawing of the product. The DPM is necessary to automatically generate disassembly sequence plans (DSPs) for product recycling and remanufacturing. Then, a modified branch and bound algorithm to automatically generate a (near) optimal DSP is presented. Since the generation

of feasible DSPs is NP-complete, the algorithm uses a branch and bound mechanism to overcome the computational burden due to otherwise exhaustive nature of the disassembly sequencing problem

Next, a new problem-which has never been addressed in the literature-, namely, the disassembly line balancing problem (DLBP), is introduced. Its objective is to improve the flow of parts in the disassembly system in a way such that both the utilization of the disassembly line is maximized and the demand for the parts retrieved from the returned products is met. A classification of important considerations related to the DLBP is given. A heuristic is presented to solve the DLBP under several assumptions. The heuristic is based on a priority function which is instrumental in identifying the "best" task to assign to a particular workstation. Later, a solution approach is given to solve the DLBP in the presence of task failures. Examples are presented to illustrate the algorithmic solution methods proposed for DSP generation and DLBP solution.

- Gupta, S. M. and Veerakamolmal, P., "A Case-Based Reasoning Approach for the Optimal Planning of Disassembly Processes", ***Proceedings of the Second International Seminar on Reuse***, Eindhoven, The Netherlands, March 1-3, pp. 141-150, 1999.

Abstract— The complexity of planning for disassembly, as well as the time required, increases with the number of components in a product. Furthermore, in dealing with a multiple products situation, it is important to have the capability to create disassembly process plans quickly in order to prevent interruptions in processing. The application of case-based reasoning (CBR) approach in planning for disassembly can go a long way in avoiding interruptions in processing. CBR is a technique that allows a process planner to rapidly retrieve, reuse, revise, and retain the solution to past disassembly problems. Once a planning problem has been solved and stored in the case memory, a planner can retrieve and reuse the product's disassembly process plan any time in the future. The planner can also adapt an original plan for a new product that does not have an existing plan in case memory. Following adaptation and application, the successful plan is retained in the case memory for future use. In this paper, an approach to solve the problem of multi-product/multi-manufacturer disassembly is presented. The focus is on the procedures to initialize a case memory for different product platforms, and to operate a CBR system which can be used to plan disassembly processes.

- Veerakamolmal, P. and Gupta, S. M., "Disassembly", ***Industrial Engineering Applications and Practice: Users' Encyclopedia***, published by International Journal of Industrial Engineering - Applications and Practice, ISBN 0-9654 506-0-0, 1999.

Abstract— Product manufacturers are subject to numerous and often contradicting demands. The array of demands include functionality, cost effectiveness, appeal, durability, timeliness and maintainability. Increasingly significant is the demand for manufacturers to keep up with consumer's appetite for cutting-edge technology. In order to be competitive, manufacturers have to develop, produce and deliver the latest production models to consumers at an astronomical rate. In turn, consumers are replacing outdated products even though they are still operational. Products ranging from electronics, home appliances, to automobiles are the growing list of used products scrapped that requires proper disposal (i.e., incineration and landfill). Furthermore, since the incinerators and landfills are becoming limited and, thus, costly to use, there is an urgency to identify alternative means of products' disposal. With increasing significance, environmental organizations and legislatures are calling on manufacturers to take responsibility, in part, for the disposal of products in an environmentally benign manner. In many parts of the world, manufacturers are urged to take-back their products and recover the components and materials at the end of their useful lives. With profits being the most important motivation for businesses, manufacturers have to face the challenge

in recovering components and materials that have some residual value, while bearing the operational costs incurred in the recovery operations. The focus these days is on developing new operational techniques on planning for component and material recovery-to reduce, reuse and recycle products and their components in the most cost efficient manner. Considerations such as the potential for component or entire assembly reclamation, reuse, remanufacture, or recycle are important at this stage. Even energy recovery to some extent can be planned if the product can be taken apart for safe incineration, therefore allowing energy to be extracted from the remaining waste. One particular requirement of a component and material recovery system is the need for disassembly prior to their retrieval, reuse, recycling, and disposal. Disassembly is the process of systematic separation of the constituent components from a product assembly. Disassembly provides the opportunity to recover and isolate valuable components and/or materials from scrap by means of manual or automatic separation processes. With stringent take-back regulations and the corresponding economic consequences, no longer is disassembly an alternative to traditional disposal methods like incineration and landfill-it is a necessity. The disassembly operations have become increasingly complex since we have to consider the return flow of products, the outgoing supply of disassembled components, and the disassembly process itself. The operational aspect of disassembly has become a problem of such importance that it has accumulated a rich body of knowledge for the study of planning for disassembly processes. Questions that are central to the disassembly operations include: How to most efficiently collect the products? How to disassemble? What is the optimal amount to disassemble? and How to dispose of unused disassembled components?

- Veerakamolmal, P. and Gupta, S. M., "A Combinatorial Cost-Benefit Analysis Methodology for Designing Modular Electronic Products for the Environment", ***Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment***, Danvers, Massachusetts, May 11-13, pp. 268-273, 1999.

Abstract— This paper presents a technique to analyze the efficiency of designing electronic products for the environment. The efficiency of each design is indicated using a Design for Disassembly Index (DfDI). DfDI uses a disassembly tree (DT) which relies on the product's bill of materials as its structural blueprint. DfDI can be used to compare the efficiency among alternative designs, identifying the best alternative for a product retirement plan. In addition, the index offers designers with an important measure to help improve future products.

- Veerakamolmal, P. and Gupta, S. M., "Analysis of Design Efficiency for the Disassembly of Modular Electronic Products", ***Journal of Electronics Manufacturing***, Vol. 9, No. 1, 1999.

Abstract— In this paper, we present a technique for analyzing the design efficiency of electronic products, in order to study the effect of end of life (EOL) disassembly and disposal on the environment. The design efficiency is measured using a Design for Disassembly Index (DfDI). DfDI uses a disassembly tree (DT) which relies on the product's structure. The DT can be used to identify the precedent relationships that define the hierarchy of the product's structure (which in turn, represents the order in which components can be retrieved). DfDI can be used to analyze the merits and drawbacks of different product designs. The index offers designers with an important measure to help improve the future products. We provide a comprehensive procedure for developing the index and demonstrate its application through an example.

- Veerakamolmal, P. and Gupta, S. M., "Automating Multiple Products Disassembly Process Planning with Case-Based Reasoning", ***Proceedings of the Second***

International Conference on Operations and Quantitative Management, Ahmedabad, India, January 3-6, pp. 24-33, 1999.

Abstract— This paper addresses the importance of planning for disassembly as a response to recent regulatory trend and increased consumers' environmental awareness. For the disassembly of a product, the size of the problem dramatically increases as the number of components increases. When planning involves multiple products, yet another layer of complexity is added to the problem. The proposed technique, case-based reasoning (CBR), is an approach to solve the problem of multiple products disassembly. CBR is a technique that allows a process planner to establish, store, reuse, and/or adapt the solution to past disassembly problems. Once a product has been initialized (established) and maintained in the case memory, a planner is allowed to search and retrieve (reuse) the product's disassembly process plan. If a product does not exist in the case memory, the planner can retrieve a product structure that is similar to the new one and make the necessary adjustments (adaptation). A derived plan can then be quickly optimized for processing. This way, a disassembly facility can operate efficiently in a multiple products reclamation system.

- Veerakamolmal, P. and Gupta, S. M., "Designing Electronics Products for Disassembly Using Benefit/ Cost Analysis", **Proceedings of the 1999 Annual Meeting of the Northeast Decision Sciences Institute**, Newport, Rhode Island, March 24-26, pp. 189-191, 1999.

Abstract— This paper presents a technique to analyze the design efficiency of a product at both ends of the life-cycle. The design efficiency is measured using a Design for Disassembly Index (DfDI). DfDI uses a disassembly tree (DT) which relies on product's structural blueprint. The DT can be used to identify precedent relationships that define the structural constraints in terms of the order in which components can be retrieved. DfDI can be used to compare the merits and drawbacks of different product designs. The index offers designers with an important measure to help improve future products. We provide a comprehensive procedure for developing the index and demonstrate its application through an example.

- Veerakamolmal, P. and Gupta, S. M., "Reusable-Component Requirements Planning for the Integrated Remanufacturing System", **Proceedings of the 25th International Conference on Computers and Industrial Engineering**, New Orleans, Louisiana, March 29-April 1, pp. 58-61, 1999.

Abstract— In this paper, we propose a methodology to determine the number of products to disassemble in order to fulfill the demand of various components for remanufacturing. A modification of the material requirements planning (MRP) technique is used to determine the number of components needed to remanufacture products in different time periods. An example is presented to illustrate the technique.

- Veerakamolmal, P., "Design and Analysis of Disassembly and Remanufacturing Systems in the Electronics Industry", **PhD Thesis**, (Advisor: Dr. S. M. Gupta), Department of Mechanical, Industrial and Manufacturing Engineering, Northeastern University, June 1999.

Abstract— Interest in the area of disassembly and remanufacturing in the electronics industry has intensified in recent years. The abundance of used products scrapped has triggered a demand for reusable electronic components, priced at a fraction of the new components. As a result,

manufacturers have started to realize that they must turn their attention to the development of new methodologies for reverse logistics. This dissertation addresses this need.

The reverse logistics problem encompasses many different characteristics of environmentally conscious manufacturing and planning, including disassembly, reuse, recycling, and remanufacturing. Reverse logistics is gaining increased attention not only because of environmental factors but also for economic reasons.

In this research, five main techniques are employed to solve five different problems.

The first technique addresses the need for designing products for disassembly. Product design is the dominant factor that influences the ease by which the product can be taken apart at the end of its life. All efforts involved in reverse logistics would be futile without initially designing products for disassembly. The technique involves solving the problem in one of two ways. The first way enumerates the different combinations for retrieving the components based on an objective function consisting of four variables in order to find the largest value of the Design for Disassembly Index (DfDI). The second way employs an Integer Programming (IP) approach to find the optimal DfDI.

The second technique develops a heuristic scheduling methodology to solve the sequencing of a two-stage disassembly/retrieval process. A scheduling heuristic is used to optimize the processing time of the overall process with respect to the product structure. The uniqueness of this approach is that it allows a process planner to breakdown the product's bill-of-materials into modules, each consisting of functional component groups. The heuristic first optimizes the processing time of each stage (resulting in an optimal sub-sequence) and later combines the sub-sequences to make a complete optimal disassembly/retrieval process plan.

The third technique uses Case-Based Reasoning (CBR) to quickly generate disassembly process plans in order to prevent interruptions during disassembly operations. CBR is a technique which allows a process planner to rapidly retrieve, reuse, revise, and retain solutions to past disassembly problems. As a result, CBR allows uninterrupted disassembly of a variety of products in a multiple-product/ multiple-manufacturer environment.

The fourth technique addresses the lot-sizing problem for product disassembly. For disassembly, reverse logistics usually consists of a mixed batch of products. Since different products yield different combinations of components, finding an optimal lot-size of products to disassemble is often desired. In this dissertation, this problem is solved using Integer Programming. The final technique optimizes a bi-directional supply chain system using a sophisticated reverse flow (from the end of lease, end-of-life, and/or returned products) for product remanufacturing. With a forecasted demand for certain remanufactured items within a planning horizon, the technique uses a modification of the Materials Requirements Planning (MRP) approach to find the number of components to retrieve in different periods for remanufacturing. After remanufacturing, the "like-new" products are reintroduced back to consumers.

In sum, the above-mentioned innovative approaches to problems associated with reverse logistics, lead to optimum use of resources without compromising the quality of our environment.

2000

- Aksoy, H. K. and Gupta, S. M., "Buffer Allocation Plan for Cellular Remanufacturing Systems", ***Proceedings of the 2000 World Symposium on Group Technology/ Cellular Manufacturing***, San Juan, Puerto Rico, March 27-29, pp. 239-244, 2000.

Abstract— In this paper, we present a near optimal buffer allocation plan specifically developed for cellular remanufacturing system. To this end, we propose an algorithm for the analysis of the system. The algorithm analyzes the system using an open queueing network with finite buffers and unreliable machines. The remanufacturing system considered here consists of three stations, viz., a disassembly and testing station for returned products, a disposition station for non-reusable returns and a remanufacturing station. In order to analyze the queueing network, we use the decomposition principle and expansion methodology. Finally, the buffer allocation algorithm distributes the given number of available buffer slots among the three stations to optimize the system's performance.

- Aksoy, H. K. and Gupta, S. M., "Effect of Reusable Rate Variation on the Performance of Remanufacturing Systems", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 13-20, 2000.

Abstract— In this paper, we investigate the variation in the reusable rate of cores (used products) on the performance of the remanufacturing system. The remanufacturing system considered here consists of three modules; viz., the disassembly and testing module for returned products, the disposition module for non-reusable returns, and the remanufacturing module. Each server in the system is subject to breakdown and has a finite buffer capacity. Repair times, breakdown times and service times follow exponential distributions. We model the remanufacturing system as an open queueing network and use the decomposition principle and expansion methodology to analyze it.

- Aksoy, H. K. and Gupta, S. M., "Near Optimal Buffer Allocation Plan for Remanufacturing Systems", ***Proceedings of the 2000 Annual Meeting of the Northeast Decision Sciences Institute***, Atlantic City, New Jersey, March 22-24, pp. 111-113, 2000.

Abstract— A remanufacturing system is prone to inefficiencies because of built-in uncertainties and complexities of the nature of the operations. One way to improve the performance of the system is to distribute a given number of available buffer slots among the stations in a strategic manner. In this paper we present a near optimal buffer allocation plan (NOBAP) specifically developed for remanufacturing systems. To this end, we introduce an algorithm that analyzes the system using an open queueing network with finite buffers and unreliable machines. In order to analyze the queueing network, we use the decomposition principle and expansion methodology. The results obtained by using the algorithm are compared with the ones found using the exhaustive search. The results show that the NOBAP is very rigorous and remarkably accurate.

- Boon, J. E., Isaacs, J. A. and Gupta, S. M., "Economics of PC Recycling", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 29-35, 2000.

Abstract— As the use of personal computers (PCs) increases, their short life cycle and the fact that they contain many hazardous materials means that their retirement and disposal represents a significant environmental concern. Many communities are mandating the recycling of these PCs, to recover parts and materials, and to minimize the amount of waste landfilled or incinerated. An industry to recycle these PCs is evolving to take advantage of this stream of materials. At present, PC recycling is not profitable. This paper investigates the factors that most influence the net cost to recycle PCs so that PC manufacturers, recyclers and legislators may better develop products and policies to insure that it is cost effective to recycle PCs.

- Boon, J., Isaacs, J. and Gupta, S. M., "Economic Impact of Aluminum Intensive Vehicles on the US Automotive Recycling Infrastructure", ***Journal of Industrial Ecology***, Vol. 4, No. 2, 117-133, 2000.

Abstract— The use of aluminum alloys in automobile production is growing as automakers strive to lower the fuel consumption of their vehicles and reduce emissions by substituting aluminum for steel in many applications. The current recycling infrastructure for end-of-life (EOL) vehicles is mature, profitable, and well suited to steel intensive vehicles; however, increased use of cast aluminum and expanded use of wrought aluminum will present new challenges and opportunities to the disassembler and shredder, who now comprise the first stages of the vehicle recycling infrastructure.

Using goal programming techniques, a model of the automobile recycling infrastructure is used to assess the materials streams and process profitabilities for several different aluminum intensive vehicle (AIV) processing scenarios. The first case simulates the processing of an AIV in the current recycling infrastructure. Various changes to the initial case demonstrate the consequences to the disassembler and shredder profitabilities when: the price of nonferrous metals changes; greater fractions of the vehicle are removed as parts; the parts removed by the disassembler have increased aluminum content; the quantity of polymer removed by the disassembler is increased; the disassembly costs increase; the disposal costs for shredder residue and hazardous materials increase; the shredder processing costs increase; and different AIV designs are considered. These profits are also compared to the profits achieved for a steel unibody vehicle to highlight the economic outcomes of introducing aluminum intensive vehicles into the existing infrastructure.

- Dincer, M., Kizilkaya, E. A. and Gupta, S. M., "Economic Analysis of End-of-Life Computer Systems in Educational Institutions", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 36-43, 2000.

Abstract— In this paper we address the operational and economical aspects of EOL computer systems at educational institutions. To this end we present an actual case study of a major university in Boston and provide an economical analysis of different options such as disposal, disassembly, recycling, reuse and re-sale of these systems. We recommend a new procedure that will improve the collection and handling processes leading to a structured decision making methodology.

- Gungor, A., Gupta, S. M., Pochampally, K. and Kamarthi, S. V., "Complications in Disassembly Line Balancing", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 289-298, 2000.

Abstract— Disassembly line is, perhaps, the most suitable way for the disassembly of large products or small products in large quantities. In this paper, we address the disassembly line balancing problem (DLBP) and the challenges that come with it. The objective of balancing the disassembly line is to utilize the disassembly line in an optimized fashion while meeting the demand for the parts retrieved from the returned products. Although, the traditional line balancing problem for assembly has been studied for a long time, so far, no one has formally talked about the DLBP. In this work, our primary objective is to address the DLBP related issues. However, we also present a heuristic to demonstrate how several important factors in disassembly can be incorporated into the solution process of a DLBP. An example is considered to illustrate the use of the heuristic.

- Gupta, S. M. and Veerakamolmal, P., "A Bi-directional Supply Chain Optimization Model for Reverse Logistics", ***Proceedings of the 2000 IEEE International Symposium on Electronics and the Environment***, San Francisco, California, May 8-10, pp. 254-259, 2000.

Abstract— This paper focuses on Supply Chain Optimization system for reverse logistics. The solution approach employs an adaptation of the Materials Requirements Planning (MRP) technique, termed as Components Requirements Planning, to determine the number of components needed to remanufacture products in each time period throughout the planning horizon.

- Gupta, S. M. and Veerakamolmal, P., "Environmental Issues: Reuse and Recycling in Manufacturing Systems", ***Encyclopedia of Production and Manufacturing Management***, Edited by Paul Swamidass, Kluwer Academic Publishers, 192-197, ISBN: 0-7923-8630-2, 2000.

Abstract— The last few years have seen a tremendous growth in the demand for durable consumer goods. The rapid development and improvement of products have given rise to additional demand resulting in shortened lifetime of most products. This in turn has increased the quantity of used products scrapped. The bulk of the scrap comes from automobiles, household appliances, consumer electronic goods, and at an increasing rate from computers. There is an urgency to find alternative ways to dispose of products because of the alarming rate at which the landfills are being used up. In addition, environmental awareness and recycling regulations have been putting pressure on many manufacturers and consumers, forcing them to produce and dispose of products in an environmentally responsible manner. In many parts of the world (and especially in Europe), the regulations are becoming more stringent and manufacturers are urged to take-back and recycle their products at the end of their useful lives. Furthermore, sometimes they are also urged to use recycled materials whenever possible. This article presents an introduction to environmental issues in manufacturing systems.

- Gupta, S. M. and Veerakamolmal, P., "A Case-Based Reasoning Approach for Optimal Planning of Multi-Product/ Multi-Manufacturer Disassembly Processes", ***International Journal of Environmentally Conscious Design and Manufacturing***, Vol. 9, No. 1, 15-25, 2000.

Abstract— The complexity of planning for disassembly, as well as the time required increases with the number of components in a product. Furthermore, in dealing with a multiple products situation, it is important to have the capability to create disassembly process plans quickly in order to prevent interruptions in processing. The application of case-based reasoning (CBR) approach in planning for disassembly can go a long way in avoiding interruptions in processing. CBR is a technique that allows a process planner to rapidly retrieve, reuse, revise, and retain the solution to past disassembly problems. Once a planning problem has been solved and stored in the case memory, a planner can retrieve and reuse the product's disassembly process plan any time in the future. The planner can also adapt an original plan for a new product that does not have an existing plan in case memory. Following adaptation and application, the successful plan is retained in the case memory for future use. In this paper, an approach to solve the problem of multi-product/multi-manufacturer disassembly is presented. The focus is on the procedures to initialize a case memory for different product platforms, and to operate a CBR system that can be used to plan disassembly processes.

- Gupta, S. M. and Veerakamolmal, P., Articles on "Disassembly", "Dry Sorting", "Green Manufacturing", "Life Cycle Assessment (LCA)", and "Remanufacturing" on

pages 163-164, 166, 258, 361-362, and 640 respectively, ***Encyclopedia of Production and Manufacturing Management***, Edited by Paul Swamidass, Kluwer Academic Publishers, ISBN: 0-7923-8630-2, 2000.

Abstract— Disassembly is the process of systematic removal of desirable constituent parts from an assembly for reuse or recycling. In addition, disassembly provides the opportunity to recover valuable materials or isolate poisonous substances from scrap by means of manual or automatic separation process. It is an alternative to traditional disposal method like incineration and landfill. Besides it adds value to the existing product because, instead of throwing it away, the products can be disassembled for refurbishment, reuse, or recycling. There are essentially two types of disassembly, viz., non-destructive and destructive. Non-destructive disassembly removes desirable parts from an assembly while ensuring that there is no impairment to the parts. Destructive disassembly, on the other hand, is the process of separating similar metals and materials from an assembly in order to sort each material type for recycling.

Dry sorting is a method of separating a mixture of different materials by distinguishing the differences in material properties, such as size or density. Materials with different particle sizes can be sorted by screening the smaller ones from the larger ones.

The term 'green' is commonly used to denote an environmental friendly activity. The objective of green manufacturing is to design and produce products in an environmentally benign manner. The characteristics of an environmentally benign product ranges from the use of recyclable materials or recycled materials wherever possible, the use of fixtures and/or components that can be easily taken apart, or the design of product structure to allow ease of disassembly.

According to the Society of Environmental Toxicology and Chemistry, Life Cycle Assessment is defined as "An objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, use/reuse/maintenance, recycling and final disposal."

Remanufacturing transforms durable products that are worn, defective, or obsolete into functional products through disassembly, cleaning, refurbishment and replacement of components, reassembling, and testing. The range of services can be: repair or replacement of broken or unreliable parts, system upgrade, minor system modification, routine system inspection, and product refurbishment to enhance appearance. A remanufactured product may retain its old form, or may lose the original identity all together.

-
- Gupta, S. M., Lee, Y. J. and Veerakamolmal, P., "A Supply Chain Optimization Approach for Reverse Logistics of End-of-Life Products", ***Proceedings of the 2000 Annual Meeting of the Northeast Decision Sciences Institute***, Atlantic City, New Jersey, March 22-24, pp. 262-264, 2000.

Abstract— In this paper, the main focus is on an optimization approach to determine the supply of a variety of products to recover (at the end of their lives) in order to fulfill the demand of an assortment of components, and have an environmentally benign policy of minimizing waste generation. When the problem is solved, it gives the number of each product type to be disassembled in order to fulfill the demand of components needed at minimal cost. From the supply chain perspective, this would result in minimal inventory requirements at both ends of the reverse logistics chain, viz., at the end-of-life (EOL) products end and at the disassembled components end.

- Gupta, S. M., Lee, Y.-J., Z. Xanthopoulos and P. Veerakamolmal, "An Optimization Approach for A Reverse Logistics Supply Chain", ***Proceedings of the 2000 World Symposium on Group Technology/ Cellular Manufacturing***, San Juan, Puerto Rico, March 27-29, pp. 227-232, 2000.

Abstract— This paper focuses on Supply Chain Optimization system for reverse logistics of products that are taken back for disassembly and retrieval of reusable components for remanufacturing. The goal is to provide a cost efficient way in which manufacturers can reclaim various models of a product for remanufacturing.

- Kizilkaya, E. A. and Gupta, S. M., "A Modified Kanban System for Disassembly", ***Proceedings of the 2000 Annual Meeting of the Northeast Decision Sciences Institute***, Atlantic City, New Jersey, March 22-24, pp. 239-241, 2000.

Abstract— We present a new Kanban system specifically developed for material control and scheduling in a disassembly environment. We briefly highlight the differences between the new (modified) and the traditional Kanban system. We assert that in the disassembly environment, the Kanban system is superior to the "push" system currently practiced in industry. To that end, we consider a case example and test its performance by experimenting with several different scenarios. In all instances, the Kanban system outperforms the "push" system.

- Kizilkaya, E. A. and Gupta, S. M., "A Pull Control System for the Disassembly Environment", ***Proceedings of the 2000 World Symposium on Group Technology/ Cellular Manufacturing***, San Juan, Puerto Rico, March 27-29, pp. 233-238, 2000.

Abstract— This paper presents a modified Kanban (pull) system for the disassembly environment and compares it to its "push" counterpart. Various scenarios are explored using a case example. For the scenarios, the assumptions, input data and results are presented. The study clearly demonstrates the effectiveness of the modified Kanban system over the push system.

- Kizilkaya, E. A., Gupta, S. M. and Nakashima, K., "A New Approach to Material Control and Scheduling in a Disassembly Environment", ***Proceedings of the Fourth International Conference on EcoBalance***, Tsubuka, Japan, October 31-November 2, 75-78, 2000.

Abstract— We present a pull system that uses a new approach to facilitate material control and scheduling in a disassembly environment and is called the modified Kanban system for disassembly (MKSD). We also compare the performance of MKSD to its "push" counterpart. Various scenarios are explored using a case example. For the scenarios, the assumptions, input data and results are presented. The study clearly demonstrates the effectiveness of the modified Kanban system over the push system.

- Kongar, E. and Gupta, S. M., "A Goal Programming Approach to the Remanufacturing Supply Chain Model", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 167-178, 2000.

Abstract— The current trend of depletion of natural resources due to an ever-increasing number of consumer goods manufactured has led to an increase in the quantity of used and outdated products discarded. From an environmental point of view, it is not only desirable to disassemble, reuse, remanufacture and/or recycle the discarded products, in many cases it can also be economically justified. This situation being the motive, in recent years there have been several studies reported on disassembly, remanufacturing and/or recycling environments. Since "environmentally conscious manufacturing" is a relatively new concept that brings new costs and profits into consideration, its analysis cannot be provided by readily available techniques. This paper presents a quantitative methodology to determine the allowable tolerance limits of planned/unplanned inventory in a remanufacturing supply chain environment based on the decision-maker's unique preferences. To this end, an integer goal-programming model that provides a unique solution for the allowable inventory level is presented. The objective of the supply-chain model is to determine the number of a variety of components to be kept in the inventory while economically fulfilling the demand of a multitude of components, and yet have an environmentally benign policy of minimizing waste generation. A numerical example is presented to illustrate the methodology.

- Kongar, E. and Gupta, S. M., "A Multi-Criteria Model for Remanufacturing", ***Proceedings of the Third International Conference on Operations and Quantitative Management***, Sydney, Australia, December 17-20, pp. 290-297, 2000.

Abstract— In this paper, we present a preemptive integer goal programming approach to model the remanufacturing process to achieve various economical, physical and environmental goals. The model allows the decision-maker to determine and sort his/her goals according to their importance. A case example is presented to illustrate the use of the model.

- Korugan, A. and Gupta, S. M., "A Kanban Control Mechanism for a Multi-Echelon Inventory System with Returns", ***Proceedings of the 2000 Annual Meeting of the Northeast Decision Sciences Institute***, Atlantic City, New Jersey, March 22-24, pp. 105-107, 2000.

Abstract— In this paper, we present a two-stage kanban control model to study a two-echelon hybrid inventory system with disposals. We then express the expected cost function for the inventory system in terms of the performance measures obtained from the analysis of the kanban model. Finally, we present the results of a series of experiments that are conducted to measure the impact of the kanban sizes on the expected total cost of the system.

- Korugan, A. and Gupta, S. M., "Price Policies for a Hybrid System with Disposals", ***Proceedings of the 2000 World Symposium on Group Technology/ Cellular Manufacturing***, San Juan, Puerto Rico, March 27-29, pp. 245-250, 2000.

Abstract— In this paper, alternative price policies for a hybrid system with disposals are studied. An expected revenue model is constructed with different revenues for remanufactured and new items. The model is then used to study the effectiveness of the price policies under different scenarios. To this end the value iteration method is used in calculation of the average total revenues for their respective scenarios.

- Korugan, A. and Gupta, S. M., "Substitution Policies for a Hybrid System", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 1-6, 2000.

Abstract— As a consequence of environmental necessities, reuse of products has recently become an important issue for production and planning. Many companies are involved in retrieving used products, where they repair, refurbish and upgrade the products in order to sell them for profit. However, the regulations for many markets do not allow manufacturers to sell remanufactured products under the same pretence as new products. Therefore, companies are forced to differentiate both the recovery and the sales activities for the remanufactured products from that of the new products. In this paper, we study the impact of this differentiation. We particularly look at the feasibility of substituting one version of the product with the other in order to satisfy the demand. In the first phase of the study, we try to find optimal switching functions for substitution decisions using a Markov decision process. In the second phase, we define several control policies and compare them with respect to the expected total cost function of the system.

- Veerakamolmal, P. and Gupta, S. M., "Design for Disassembly, Reuse and Recycling", ***Green Electronics/ Green Bottom Line: Environmentally Responsible Engineering***, Edited by Lee Goldberg, Butterworth-Heinemann; (Newnes), Chapter 5, 69-82, ISBN: 0-7506-9993-0, 2000.

Abstract— New electronic products are usually compact and equipped with the latest technology. They are replacing outdated ones at an astronomical rate. Ironically, a large number of outdated products are often in excellent condition. Rapid product development coupled with consumer appetite for latest models of products, have caused consumers to discard outdated products even though they are still operational. This in turn leads to an increase in the quantity of used and outdated products scrapped. Products made with reusable components, retrieved from discarded electronic products, are sometimes not only cheaper but also better. For example, electronic chips recovered from outdated computers could prove to be more reliable than the new chips (if care is taken to protect them from thermal damage during removal), because the reused chips would have survived the "burn-in" period. In addition, because retrieved parts are often classified as scrap, manufacturers could obtain them at a below-market cost. Reuse and recycling of electronic products have not only been driven by the return on capital concept, but also by the return to nature concept. Environmental awareness and recycling regulations have been putting pressure on manufacturers and consumers, forcing them to produce and dispose of products in an environmentally friendly manner. In many parts of the world, and especially in Europe, the regulations are becoming more stringent and manufacturers are required to recycle their products at the end of their useful lives. Current trends hold the promise for companies to do well economically as well as being environmentally friendly while meeting the impending regulations. To benefit from this new found environmentalism, electronic manufacturers have to explore possible alternatives for designing environmentally benign products. This article provides an overview of the state-of-the-art techniques for Design for Disassembly, Reuse and Recycling.

- Veerakamolmal, P. and Gupta, S. M., "Optimizing the Supply Chain in Reverse Logistics", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 157-166, 2000.

Abstract— Supply chain planning systems in reverse logistics present the industry with new problems that demand new approaches. The specific problem of the reverse logistics for the end-of-life (EOL) products addressed in this study is to determine the number of products to disassemble in a given time period to fulfill the demand of various components during that and subsequent time periods. We present a mathematical programming based model to solve the problem. When the problem is solved, it gives the number and timing of each product type to be disassembled in order to fulfill the demand of components needed at minimal disassembly and disposal costs. We illustrate the solution methodology with a case example.

- Zeid, I. and Gupta, S. M., "Disassembly Knowledge Representation via XML", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 179-185, 2000.

Abstract— Extensible markup language (XML) is a new powerful technique for Web and Internet development. It is a method of defining structured data in a text file. XML is expected to do for data what HTML has done for Web pages. XML's strength lies in its simplicity to represent data and knowledge. It can maintain hierarchical structures encountered in many systems including assemblies and disassemblies. It can also be well integrated with Java, and its Java beans. Its strength lies in its flexibility to adapt to any knowledge domain because it is a metalanguage. It is used to develop modeling languages that are tailored to specific knowledge, and specific data structures and hierarchies. This paper presents an overview of XML, followed by a proposal of an XML-based knowledge representation model for disassembly planning. An example is used to demonstrate the capabilities of the proposed XML model.

- Zeid, I., Gupta, S. M. and Pan, L., "A Case-Based Reasoning Disassembly System", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing***, Boston, Massachusetts, November 5-8, pp. 186-193, 2000.

Abstract— This paper presents a new approach to address the problem of Planning for Disassembly (PFD). The approach is based on the Case-based reasoning technique. To assist planners to solve PFD problems, a system must have some heuristics and domain specific knowledge, which is related to the representation of the disassembly knowledge. In previous work, the authors suggested to use EMOPs (Eposodic Memory Organization Packet) for the knowledge representation of the PFD plan. This paper demonstrates the implementation of the EMOP memory model. The model has been implemented in C++, and tested. An example is presented to demonstrate the capabilities of the memory model.

 **2001**

- Aksoy, H. K. and Gupta, S. M., "Capacity and Buffer Trade-Offs in a Remanufacturing System", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing II***, Newton, Massachusetts, October 28-29, pp. 167-174, 2001.

Abstract— In this paper, we examine the tradeoffs between increasing the number of buffers and increasing the capacity at the remanufacturing stations under numerous circumstances on such performance measures as expected total cost, average WIP inventory, throughput and average processing (remanufacturing) time when the remanufacturing stations are operating in uncertain environments. We model the remanufacturing system using an open queueing network with finite buffers and unreliable servers. In order to analyze the queueing network, we use the decomposition principle and expansion methodology. Each server in the system is subject to breakdown and has a finite buffer capacity.

- Aksoy, H. K. and Gupta, S. M., "Effect of Reusable Rate Variation on the Optimal Buffer Allocation for Remanufacturing Systems", ***Proceedings of the 2001 Annual***

Meeting of the Northeast Decision Sciences Institute, Pittsburgh, Pennsylvania, March 21-23, pp. 116-118, 2001.

Abstract— We investigate the effect of reusable rate variation of cores (used products) on the performance of buffer allocation plan for remanufacturing systems. We model the remanufacturing system as an open queueing network and use the decomposition principle and expansion methodology to analyze it.

- Aksoy, H. K. and Gupta, S. M., "Optimal Buffer Allocation of an Unbalanced Remanufacturing System with Unreliable Servers", **Proceedings of the 28th International Conference on Computers and Industrial Engineering**, Cocoa Beach, Florida, March 5-7, pp. 202-207, 2001.

Abstract— In this paper, we present a near optimal buffer allocation plan (NOBAP) specifically developed for a remanufacturing system with finite buffers and unreliable servers. In order to analyze the system we propose an algorithm that uses an open queueing network, decomposition principle and expansion methodology. The buffer allocation algorithm distributes the given number of available buffer slots among the remanufacturing system stations to optimize the system's performance.

- Boon, J. E., "Economic Viability of U.S. Recycling Infrastructures for End-of-Life Automotive and Electronic Products", **PhD Thesis**, (Advisors: Dr. S. M. Gupta and Dr. J. A. Isaacs), Department of Mechanical, Industrial and Manufacturing Engineering, Northeastern University, December 2001.

Abstract— Manufacturers of consumer products are now challenged to take responsibility for their products from cradle to grave. Correspondingly, end-of-life issues must be acknowledged and accommodated. Among the most sophisticated and important products to consider are vehicles and electronics. The EOL infrastructure for automobiles is mature and profitable. The disassembler and shredder are able to accommodate a wide variety of vehicles and materials, while still earning profits. The markets for secondary materials such as ferrous and nonferrous metals are well established and generate significant revenues for both the disassembler and shredder, offsetting the vehicle processing costs. However, the introduction of new materials, and changes in the markets for secondary materials may impact their profitability.

The EOL infrastructure for electronics is relatively new, and not currently profitable unless the recycler receives a processing fee. Markets for the secondary materials obtained in electronics recycling are not yet mature, and are very sensitive to over-supply, challenging the recycler's ability to obtain a predictable revenue stream. As a result, many products that could be processed are not, due to economic issues. Correspondingly, the value present in those discarded parts and materials will not be reclaimed.

Goal programming is an effective tool for evaluating the viability of an established and mature recycling infrastructure. Modifications of this approach may be employed to evaluate the viability of more variable and less mature infrastructures. Using these techniques and models of the automotive and electronics recycling industries, the importance of secondary markets to the viability of product recycling is explored. By examining the sensitivity of recycler profits to changes in revenues obtained from the sale of the various parts and materials, and by evaluating the effect of increased markets for parts, the importance of identifying and fostering markets for secondary materials is highlighted.

- Gungor, A. and Gupta, S. M., "A Solution Approach to the Disassembly Line Balancing Problem in the Presence of Task Failures", *International Journal of Production Research*, Vol. 39, No. 7, 1427-1467, 2001.

Abstract— In this paper, we discuss the disassembly line balancing problem in the presence of task failures (DLBP-F). There are precedence relationships among disassembly tasks and the tasks must be completed within a given time, which is determined by the demand in a given period. However, if a task (or more than one task) cannot be performed because of some defect, some or all of the remaining tasks may be disabled due to the precedence relationships among tasks. This may result in various complications in the flow of work-pieces on the disassembly line, e.g., early-leaving, self-skipping, skipping, disappearing and revisiting work-pieces. We discuss these complications and highlight their effects on the disassembly line. The problem is to assign tasks to workstations such that the effect of the defective parts on the disassembly line is minimized. This paper presents a solution procedure to the DLBP-F. An example is provided to illustrate the approach.

- Gungor, A. and Gupta, S. M., "Disassembly Sequence Plan Generation Using a Branch and Bound Algorithm", *International Journal of Production Research*, Vol. 39, No. 3, 481-509, 2001.

Abstract— This paper presents an approach to automatically generate disassembly sequence plans (DSPs) for product recycling and remanufacturing. We first define an algorithm to generate a geometrically-based disassembly precedence matrix (DPM) from a CAD drawing of the product. The DPM is then used to generate a hierarchical disassembly tree (HDT) which represents the feasible DSPs. Generation of the HDT, i.e., generation of all feasible DSPs, is NP-complete. Thus, in order to keep the size of the HDT manageable, we control the branching and bounding processes by using two user defined variables. The first variable, w , controls the enumeration of the HDT, while the second variable, v , controls the bounding procedure in the HDT along with an evaluation function. The evaluation function incorporates tool changes, changes in direction of movement during disassembly along with individual part characteristics (e.g., high-valued parts, parts with hazardous content, etc.) The resulting HDT is called the reduced HDT (RHDT) since it only represents as many (near-) optimum DSPs as the size of v . Experimental results are presented to demonstrate the applicability and effectiveness of the methodology.

- Gupta, S. M. and Gungor, A., "Product Recovery Using a Disassembly Line: Challenges and Solution", *Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment*, Denver, Colorado, May 7-9, pp. 36-40, 2001.

Abstract— Disassembly plays an important role in product recovery by allowing selective separation of desired parts and materials. The disassembly line is the best choice for automated disassembly of returned products, a feature that will be essential in the future. It is, therefore, important that the disassembly line be designed and balanced so that it works as efficiently as possible. In this paper, we address the disassembly line balancing problem and the challenges that come with it.

- Gupta, S. M. and Gungor, A., "Product Recovery via a Disassembly Line", *Proceedings of the 2001 POMS-Sao Paulo Meeting*, Sao Paulo, Brazil, August 11-14, pp. 162-170, 2001.

Abstract— Disassembly plays an important role in product recovery by allowing selective separation of desired parts and materials. In this paper, we address the disassembly line balancing problem

(DLBP) and the challenges associated with it. We also present a methodology to solve a simple DLBP. An example is considered to illustrate the use of the methodology.

- Gupta, S. M. and Kizilkaya, E., "Disassembly Kanban System", ***Proceedings of the 2001 POMS-Sao Paulo Meeting***, Sao Paulo, Brazil, August 11-14, pp. 356-362, 2001.

Abstract— In this paper we present a new Kanban system specifically developed for the disassembly environment. We highlight its complexities and the way to overcome them. We show that the disassembly Kanban system is superior to the "push" system currently practiced in industry. An example is considered to demonstrate this superiority.

- Gupta, S. M. and Kongar, E., "A Disassembly-To-Order System", ***Proceedings of the 2001 POMS-Sao Paulo Meeting***, Sao Paulo, Brazil, August 11-14, pp. 331-338, 2001.

Abstract— In this paper, a disassembly-to-order algorithm that incorporates the retrieval and disassembly of used products to satisfy a certain demand for products, parts and/or materials, while achieving various financial and "environmentally benign" goals, is presented. We use graph theory and goal programming to accomplish this. An example is presented to illustrate the methodology.

- Gupta, S. M. and Veerakamolmal, P., "Aggregate-Planning for End-of-life Products", ***Greener Manufacturing and Operations: From Design to Delivery and Back***, Edited by Joseph Sarkis, Greenleaf Publishing Ltd., Sheffield, U.K., Chapter 14, 205-222, ISBN: 1-8747-1942-X, 2001.

Abstract— This chapter presents a mathematical programming based model to solve the aggregate-planning problem for End-Of-Life (EOL) products. The goal is to provide a way in which the disassembler can reclaim various models of a product for remanufacturing in the most economical way. The approach is employed in a multi-period environment to determine the number of components needed to remanufacture products in each time period throughout the planning horizon. When the problem is solved, it gives the number and timing of each product type to be disassembled in order to fulfill the demand of components needed at minimal disassembly and disposal costs. Hence, from the aggregate-planning perspective, this would result in minimal inventory requirements at both ends of the processing chain (viz. the supply of EOL products and the disassembled components). The application of the optimization approach is illustrated with the help of an example.

- Isaacs, J. A. and Gupta, S. M., "Product Design Optimization and Recycling Economics", ***The Encyclopedia of Materials: Science and Technology***, Edited by K. H. J. Buschow, R. W. Cahn, M. C. Flemings, B. Illschner, E. J. Kramer, and S. Mahajan, Elsevier Science, 7887-7893, ISBN: 0-08-043152-6, 2001.

Abstract— Product designers have always had to balance various performance requirements and cost in their designs for new products. More recently, designers have also had to consider the environmental impact of product design. Such concerns have led to the emergence of environmental design initiatives that consider the production processes and the total life cycle of the product. Examination of the recycling economics of EOL products indicates that there are many factors that have an effect on the recycling infrastructures. Using systems approaches, various tools have been

developed to investigate the consequences of design alternatives and the subsequent effect on recycling economics. In this article, the results from an investigation of alternative materials in automotive bodies and the consequent recycling economics are presented as an example of the use of one of these tools.

- Kongar, E. and Gupta, S. M., "A Multi-Criteria Approach for Remanufacturing Model in a Disassembly-To-Order System", ***Proceedings of the 2001 Annual Meeting of the Northeast Decision Sciences Institute***, Pittsburgh, Pennsylvania, March 21-23, pp. 221-223, 2001.

Abstract— We present a disassembly-to-order system applied in a multi-period environment where the products are taken back from the last user and/or collectors, disassembled for the retrieval of reusable items and resold (or used) in order to meet a certain level of demand for components or subassemblies. The surplus items are recycled, stored for use in subsequent periods or properly disposed of while the surplus products are only stored for subsequent periods or disposed of. We assume that the items have finite shelf lives after which they must be disposed of. Another assumption has to do with space limitation. Thus, it is not always possible to store all items in inventory even if they have positive shelf lives. We model the problem using goal programming (GP) so that there is a balance between environmental as well as economical issues. A numerical example is provided to illustrate the methodology.

- Kongar, E. and Gupta, S. M., "Decision-Maker-Centered Disassembly Process Planning", ***Proceedings of the 28th International Conference on Computers and Industrial Engineering***, Cocoa Beach, Florida, March 5-7, pp. 208-213, 2001.

Abstract— This paper presents a multi-criteria model for the information and product flow in a disassembly-to-order environment. We assume that the used products are retrieved from the last user and/or collector and are disassembled in order to satisfy a certain demand for products, parts or materials while achieving various financial and "environmentally benign" goals.

- Kongar, E. and Gupta, S. M., "Genetic Algorithm for Disassembly Process Planning", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing II***, Newton, Massachusetts, October 28-29, pp. 54-62, 2001.

Abstract— When a product reaches its end-of-life, there are several options available for processing it including reuse, remanufacturing, recycling, and disposing (the least desirable option). In almost all cases, a certain level of disassembly may be necessary. Thus, finding an optimal (or near optimal) disassembly sequence is crucial to increasing the efficiency of the process. Disassembly operations are labor intensive, can be costly, have unique characteristics and cannot be considered as reverse of assembly operations. Since the complexity of determining the best disassembly sequence increases with the increase in the number of parts of the product, it is extremely crucial that an efficient methodology for disassembly process planning be developed. In this paper, we present a genetic algorithm for disassembly process planning. A case example is considered to demonstrate the functionality of the algorithm.

- Kongar, E. and Gupta, S. M., "Multi-Objective Optimization of Lot Size Balancing for Multi Products Selective Disassembly," ***Multiple Criteria Decision Making in the New Millennium***, Edited by Murat Koksalan and Stanley Zionts, Springer-Verlag,

Lecture Notes in Economics and Mathematical Systems, Vol. 507, Berlin, Germany, pp. 338-347, ISBN: 3-540-42377-X, 2001.

Abstract— This paper presents a mixed integer goal-programming model that provides a solution for planning component recovery from products with component commonality. The objective of the component recovery model is to determine the aggregate number of a variety of products to disassemble in order to economically fulfill the demand of a multitude of components, and yet have an environmentally benign policy of minimizing waste generation. A numerical example is presented to illustrate the methodology.

- Korugan, A. and Gupta, S. M., "A Single Stage Kanban Control System with Static Routing", ***Proceedings of the 2001 Annual Meeting of the Northeast Decision Sciences Institute***, Pittsburgh, Pennsylvania, March 21-23, pp. 227-229, 2001.

Abstract— We consider a system with two discrete production lines where the output of each one can fulfill the demand for the same type of product. An example to this case is the hybrid-manufacturing environment, where a company manufactures new products and remanufactures returned products to meet the demand. The interarrival times for demand occurrences and service completions are exponentially distributed i.i.d. variables. Here, a single stage pull production control with two types of kanbans is utilized to model the system where a kanban type is dedicated for either manufacturing or remanufacturing process.

- Korugan, A. and Gupta, S. M., "A Single Stage Kanban Control System with Dynamic Routing", ***Proceedings of the 28th International Conference on Computers and Industrial Engineering***, Cocoa Beach, Florida, March 5-7, pp. 214-219, 2001.

Abstract— In this paper, we consider a system with two discrete production lines where either one can satisfy the demand for the same type of product. An example to this case is the hybrid-manufacturing environment, where a company manufactures new products and remanufactures returned products to meet the demand. The interarrival times for demand occurrences and service completions are exponentially distributed i.i.d. variables. We model this system by using a single stage pull production control with a single type of 'K' kanbans and a routing probability 'r' to distribute the detached kanban when a demand is met.

- Korugan, A. and Gupta, S. M., "Adaptive Kanban Control Mechanism for a Single Stage Hybrid System", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing II***, Newton, Massachusetts, October 28-29, pp. 175-182, 2001.

Abstract— In this paper, we consider a hybrid manufacturing system with two discrete production lines. Here the output of either production line can satisfy the demand for the same type of product without any penalties. The interarrival times for demand occurrences and service completions are exponentially distributed i.i.d. variables. In order to control this type of manufacturing system we suggest a single stage pull type control mechanism with adaptive kanbans and state independent routing of the production information.

- Moore, K. E., Gungor, A. and Gupta, S. M., "Petri Net Approach to Disassembly Process Planning for Products with Complex AND/OR Precedence Relationships", *European Journal of Operational Research*, Vol. 135, No. 2, 428-449, 2001.

Abstract— We present a Petri net-based approach to automatically generate disassembly process plans for product recycling or remanufacturing. We define an algorithm to generate a geometrically-based disassembly precedence matrix (DPM) from a CAD drawing of the product. We then define an algorithm to automatically generate a disassembly Petri net (DPN) from the DPM; the DPN is live, bounded, and reversible. The resulting DPN can be analyzed using the reachability tree method to generate feasible disassembly process plans (DPPs), and cost functions can be used to determine the optimal DPP. Since reachability tree generation is NP-complete, we develop a heuristic to dynamically explore the (likeliest lowest cost branches of the tree, to identify optimal or near-optimal DPPs. The cost function incorporates tool changes, changes in direction of movement, and individual part characteristics (e.g., hazardous). An example is used to illustrate the procedure. This approach can be used for products containing AND, OR, and complex AND/OR disassembly precedence relationships.

- Zeid, I. and Gupta, S. M., "Computational Algorithm to Evaluate Product Disassembly Cost Index", *Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing II*, Newton, Massachusetts, October 28-29, pp. 23-31, 2001.

Abstract— Environmentally conscious manufacturing is an important paradigm in today's engineering practice. Disassembly is a crucial factor in implementing this paradigm. Disassembly allows the reuse and recycling of parts and products that reach their "death" after their life cycle ends. There are many questions that must be answered before a disassembly decision can be reached. The most important question is economical. The cost of disassembly versus the cost of scrapping a product is always considered. This paper develops a computational tool that allows decision-makers to calculate the disassembly cost of a product. The tool makes it simple to perform "what if" scenarios fairly quickly. The tool is Web based and has two main parts. The front-end part is a Web page and runs on the client side in a Web browser while the back-end part is a disassembly engine (servlet) that has disassembly knowledge and costing algorithms and runs on the server side. The tool is based on the client/server model that is pervasively utilized throughout the World Wide Web. An example is used to demonstrate the implementation and capabilities of the tool.

2002

- Boon, J. E., Isaacs, J. A. and Gupta, S. M., "Economic Sensitivity for End of Life Planning and Processing of Personal Computers", *Journal of Electronics Manufacturing*, Vol. 11, No. 1, 81-93, 2002.

Abstract— As the use of personal computers (PCs) increases, their short life cycle and the fact that they contain many hazardous materials have a significant influence on finding economical and environmentally benign means for their retirement and disposal. Many communities are mandating the recycling of these PCs to recover parts and materials and to minimize the amount of waste landfilled or incinerated. An industry to process end-of-life PCs is evolving to take advantage of this stream of materials. At present, PC recycling is not profitable unless the recycler receives a processing fee. In this paper, the factors that most influence the profitability of end of life processing of PCs are investigated and reported so that PC manufacturers and legislators may better develop products and policies to ensure that there is a viable PCs recycling infrastructure.

- Gungor, A. and Gupta, S. M., "Disassembly Line in Product Recovery", ***International Journal of Production Research***, Vol. 40, No. 11, 2569-2589, 2002.

Abstract— There are several situations in a product recovery environment where products may be disassembled for economical and regulatory reasons. The disassembly line is perhaps the most suitable setting for disassembly of large products (consisting of numerous components) as well as small products received in large quantities. In this paper, we discuss the importance of disassembly line in product recovery. The objective of the disassembly line is to utilize the available resources as efficiently as possible while meeting the demand for recovered parts. However, there are many complicating matters that need to be considered to create an efficient disassembly line. Our primary goal of this research is to discuss these issues and provide a better understanding of the complications and their effects on the disassembly line. We also demonstrate how some important factors in disassembly can be accommodated to balance a paced disassembly line by modifying the existing concept of assembly line balancing. An example is presented to illustrate the approach.

- Kongar, E. and Gupta, S. M., "A Multi-Criteria Decision Making Approach for Disassembly-to-Order Systems", ***Journal of Electronics Manufacturing***, Vol. 11, No. 2, 171-183, 2002.

Abstract— In this paper we present a multi-criteria optimization model of a disassembly to order system to determine the best combination of the number of each product type to be taken back at the end-of-life and disassembled to meet the demand for items and materials retrieved from them under a variety of physical, financial and environmental constraints so as to achieve the preemptive goals of maximum total profit, maximum sales from materials, minimum number of disposed items, minimum number stored items, minimum cost of disposal and minimum cost of preparation, in that order. When solved, the model provides the number of reused, recycled, stored and disposed items as well as the values of a host of other performance measures. A case example is presented to illustrate the model's implementation.

- Kongar, E. and Gupta, S. M., "Disassembly-To-Order System Using Linear Physical Programming", ***Proceedings of the 2002 IEEE International Symposium on Electronics and the Environment***, San Francisco, California, May 6-9, pp. 312-317, 2002.

Abstract— One of the most responsible ways of processing end-of-life (EOL) products is to minimize their disposal to landfills by reusing, remanufacturing and/or recycling them. Often, this necessitates a certain level of disassembly. It is therefore necessary to plan disassembly processing efficiently so as to minimize costs and the amount of disposal as well as to maximize reuse, remanufacturing and recycling. In this paper, we present a disassembly-to-order system to determine the number of EOL products to process to fulfill a certain demand for products, parts and/or materials under a variety of objectives and constraints using a newly developed decision tool, called Linear Physical Programming. It addresses problems involving multiple objectives and constraints and allows the decision maker to express his/her value-system in a realistic manner for each objective of interest. The model also provides the number of items to be disassembled for remanufacturing, recycling, storage and disposal. A case example is also presented.

- Lambert, A. J. D. and Gupta, S. M., "Demand-Driven Disassembly Optimization for Electronic Products", ***Journal of Electronics Manufacturing***, Vol. 11, No. 2, 121-135, 2002.

Abstract— In this paper, we address the problem of demand driven disassembly used to determine the optimal lot-sizes of end-of-life (EOL) products to disassemble so as to fulfil the demand of various components from a mix of different product types that have a number of components and/or modules in common. We discuss two approaches, viz., (1) the disassembly graph approach that is based on the study of the disassembly of mechanical products, and (2) the component-disassembly optimisation model that focuses on parts recovery by applying the reverse bill of materials. Although elegant, the main disadvantages of these two approaches are redundancy and non-linearity respectively. To overcome these disadvantages, we propose a new method that combines the advantages of both approaches without their disadvantages. This is called the tree network model, which is a linear description of the demand driven, multiple product problem that includes commonality and multiplicity. Because of its simple structure, it can also be applied in dynamic situations, which is useful in problems that are related to production planning and inventory control in reverse logistics.

- Veerakamolmal, P. and Gupta, S. M., “A Case-Based Reasoning Approach for Automating Disassembly Process Planning”, *Journal of Intelligent Manufacturing*, Vol. 13, No. 1, 47-60, 2002.

Abstract— One of the first processes for preparing a product for reuse, remanufacture or recycle is disassembly. Disassembly is the process of systematic removal of desirable constituents from the original assembly so that there is no impairment to any useful component. As the number of components in a product increases, the time required for disassembly, as well as the complexity of planning for disassembly rises. Thus, it is important to have the capability to generate disassembly process plans quickly in order to prevent interruptions in processing especially when multiple products involved. Case-based reasoning (CBR) approach can provide such a capability. CBR allows a process planner to rapidly retrieve, reuse, revise, and retain solutions to past disassembly problems. Once a planning problem has been solved and stored in the case memory, a planner can retrieve and reuse the product's disassembly process plan at any time. The planner can also adapt an original plan for a new product, which does not have an existing plan in case memory. Following adaptation and application, a successful plan is retained in the case memory for future use. This paper presents the procedures to initialize a case memory for different product platforms, and to operate a CBR system, which can be used to plan disassembly processes. The procedures are illustrated using examples.

LRM Contact Information

Dr. Surendra M. Gupta, PE
Laboratory for Responsible Manufacturing
334 SN, Dept. of MIME
Northeastern University
360 Huntington Avenue
Boston, MA 02115, USA

Phone : (617)-373-4846
Fax : (617)-373-2921
E-mail : gupta@neu.edu
Web : <http://www.coe.neu.edu/~smgupta/>
