Viable Plastics Recycling From End-of-Life Electronics

Xiuli Qu, Julie Ann Stuart Williams, and Edward R. Grant

***Abstract*—Millions of end-of-life (EOL) electronic products represent more than one million tons of engineering thermoplastics. The economically and environmentally sound recovery of engineering thermoplastics from EOL electronics is a challenge to the sustainability of electronics manufacturing. In this paper, we review the technologies to separate and identify pure post-consumer plastics from EOL electronics, which are followed by the comparison of electronic plastics recycling processes and the network models for plastics recycling processes. We also review successful plastics recycling practices for electronics. In addition, further research directions for recycling plastics from EOL electronics are discussed.**

***Index Terms*—Disassembly, end-of-life (EOL) electronics, identification, plastics recycling, separation.**

I. Introduction

MORE than 400 million electronic products per year will reach the end of their lives by 2010 according to estimates from the International Association of Electronics Recyclers [23]. As new electronic component prices plummet, fewer end-of-life (EOL) electronic components are recycled for reuse. A small fraction is processed for metals recovery; the remainder are stored or disposed. EOL electronics represent not only more than a billion pounds of metals, but also a stream of engineering thermoplastics that approaches a material equivalent to the petrochemical output of the North Slope of Alaska [57]. The consumption of petroleum resources for plastics production and the accumulation of plastic wastes from EOL electronics present well-known challenges to the sustainability of contemporary manufacturing [18], [32]. Recycling rate is one of 35 indices for sustainability [58]. Concerns over fast increasing electronic waste, consumption of nonrenewable resources, hazardous materials in electronics, and rapidly consumed landfill space have prompted governments to develop stiffer regulations for recycling electronic waste [16], [40].

While EOL electronics are currently processed to remove hazardous materials and recover metals, the economically and environmentally sound recovery of their plastic content remains as a fundamental problem that is being explored by many researchers and practitioners around the world [34], [42]. Plastics, in general, represent a highly refined material with a relatively low degree of degradation in use. For example, post-consumer high-impact polystyrene (HIPS) and blends of virgin and post-consumer HIPS have been shown to exhibit similar rheological properties to virgin HIPS [44], [60]. Likewise, mechanical recycling leaves unchanged the thermal properties of HIPS, such as glass transition temperature, deflection temperature under flexural load, and fluid index [10], [44]. However, most mechanical properties of post-consumer resin decrease due to the decrease in molecular weight caused by the thermomechanical processing in recycling [10], [44]. Nonetheless, examples of successful plastics recycling from EOL electronic components are increasing. For instance, Poh argues that a blend of 75% purified polyethylene terephthalate (PET) bottle grade and 25% purified used Hewlett Packard (HP) ink cartridges exhibits comparable properties to virgin glass-fiber filled PET, and can be used to mold HP's printer parts [37].

Because thermoplastics can be readily remolded, recovered resins may substitute for virgin resins in many applications. It is thus worthwhile to examine the technologies available to produce pure post-consumer resins from EOL electronics, including the disassembly tools for electronic housings, plastic identification tools, and mechanical and chemical plastic separation processes.

II. Technologies for Recycling Plastics From Electronics

The technologies to recycle plastics from electronics are classified into four categories:

1) disassembly tools and systems;
2) plastic identification;
3) mechanical plastic separation;
4) chemical plastic separation.

The technologies to recover plastics from EOL electronics in the literature are summarized in Table I.

A. Disassembly Tools and Systems

Disassembling the plastic components in electronics prior to bulk recycling improves the purity and value of recycled engineering plastics. Yu *et al.* present a generic decision-making methodology to generate optimal and alternative recycling plans for various electronics scrap materials or components [63]. Rios and Stuart present new scheduling rules for plastics demand-driven disassembly processes [43]. Despite abundant literature in the manual or automated disassembly of electronic components [19], [30], [51], few studies have focused on the disassembly of plastics [52].

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X. Qu is with the School of Industrial Engineering, Purdue University, West Lafayette, IN 47907 USA.

J. A. S. Williams is with the Department of Management and Management Information Systems, University of West Florida, Pensacola, FL 32514 USA.

E. R. Grant is with the Chemistry Department, University of British Columbia, Vancouver, BC V6T 1Z4 Canada.

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TABLE I
SUMMARY OF TECHNOLOGIES TO RECOVER PLASTICS FROM EOL ELECTRONICS

Technology	Specific technology	Capabilities	Limitations	References
Disassembly tools and systems	Selective disassembly policies	Quick-to-use policies call for removal of select plastics components	Since the policies apply to product categories, they may not optimize disassembly for a specific product	[53]
	Symbols for manual disassembly	The symbols reduce manual disassembly time to remove plastic housings.	The symbols do not include the information to recover internal plastic components.	[41]
	Flexible unscrewing tool for disassembly	The tool has a shape-independent end-effector.	Locating screws are still required for disassembly.	[6]
Plastics identification	X-ray fluorescence spectroscopy	X-ray fluorescence spectroscopy separates PVC from PET with high accuracy.	The high accuracy is not applicable to the separation of other polymers.	[21], [49]
	Near infrared (NIR) spectroscopy	NIR spectroscopy identifies plastics quickly.	NIR spectroscopy can not identify dark colored plastics, and can not identify HDPE from LDPE.	[17], [21]
	Mid-infrared (MIR) spectroscopy	MIR spectroscopy can distinguish a variety of plastics with close chemical structures regardless of their colors.	MIR spectroscopy is sensitive to the surface state of the object identified.	[1], [12], [49]
	Infrared laser impulse thermography	Infrared laser impulse thermography can rapidly identify 22 types of engineering plastics regardless of their thickness, color, and aging.	It is necessary to establish reference libraries preceding the plastics identification using infrared laser impulse thermography.	[50]
	Raman spectroscopy	Raman spectroscopy can reliably and quickly identify a wide rage of polymer types regardless of their colors.	Reference library in calibration with operating conditions must be established for the plastics identification using Raman spectroscopy.	[1], [17], [21], [29], [49]
Mechanical plastics separation	Air classification	Air classification is a high throughput plastics separation method based on density.	Separation efficiency is limited if particle sizes are nonuniform or mixed plastic densities are similar.	[55]
	Hydrocycloning	Hydrocycloning is a high throughput plastics separation method based on density.	Separation efficiency is limited if particle sizes are nonuniform or mixed plastic densities are similar.	[9], [45], [55]
	Float-sink separation	Float-sink is a plastics separation method based on density.	The separation efficiency is limited if mixed plastic particles have similar densities.	[55]
	Flotation separation	Flotation is a plastics separation method based on the difference in plastic surface properties.	The separation efficiency is sensitive to particle sizes, shapes, surface properties, and wetting agents.	[45-47]
	Electrostatic separation	Electrostatic separation utilizes the difference in triboelectric properties of plastics.	The separation efficiency is sensitive to charging surface and time, air velocity, relative humidity and temperature, and electric field strength.	[15], [59]
Chemical plastics separation	Pyrolysis	Pyrolysis decomposes mixed plastics into gas, oil, and residue at high temperature in the absence of oxygen.	The separation method is energy intensive due to the high temperature (600 – 900°C) required.	[25], [26], [39]
	Gasification	Gasification converts plastics to gas and residue using high temperature and rapid cooling.	The process requires high temperature (1150°C) and rapid cooling (~50°C).	[61]

Stuart *et al.* develop an alternative approach that accounts for product model proliferation and the ensuing variety of products arriving in recycling centers [53]. Their disassembly policies consider aggregated product groups, such as computers, printers, and monitors. For general product categories, the ratio of the quantity of plastic recovered to the time required for disassembly for each plastic part is used to determine the depth of plastics disassembly. Based on experimental results, the authors propose a selective disassembly strategy, calling for removal of the back cover on monitors and televisions and removal of the entire cover on printers and computers. The plastic separation rate of the proposed strategy is as high as 1.3 kg/min, but the disassembly depth is significantly smaller than that called for in [8], [13], [27]. The results demonstrate that their selective disassembly policy is effective for a variety of computer, printer, and monitor models, typifying the random product distributions arriving at electronics recycling facilities [42].

The diversity of EOL electronics received by electronics recycling centers is a major obstacle to the automated disassembly of plastic components [31]. As a result, most electronics recycling centers choose manual disassembly, which is sometimes assisted by power tools.

Manual disassembly is labor intensive, which results in high costs. The cost of manual disassembly depends on the average disassembly time per product. Rios *et al.* introduced the concept of design symbols to help disassembly workers to more quickly assess product complexity with respect to location and number of fasteners [41].

The diversity of EOL electronics and the variety of joints within these electronics require a number of different tools to disassemble the plastic housings. Frequent tool changes increase the average time to disassemble a product. Various disassembly tooling mechanisms are reviewed in [52]. For example, Basdere and Seliger designed a flexible unscrewing tool with a shape-independent end-effector, which creates its own acting surfaces using a high-frequency impact mechanism [6]. The flexible unscrewing tool is adapted to all screw head shapes and sizes. Fast whole plastic part disassembly is essential to plastics recycling economics.

There are more than ten types of plastics found in EOL electronics [5], [20]. As a result, the plastic pieces disassembled from EOL electronics need to be sorted. Although most plastic pieces are marked to indicate their type, a significant number of pieces are mismarked [3]. Therefore, accurate identification technologies are needed to determine the plastic type for each plastic piece as discussed next.

B. Plastics Identification Technologies

Plastics identification may be conducted on single parts or on a mixture of parts during bulk mechanical separation. In this section, we focus on using part methods which include X-ray fluorescence spectroscopy, Infrared spectroscopy, and Raman spectroscopy.

X-ray fluorescence spectroscopy can sort polyvinyl chloride (PVC) plastics from PET plastics with an accuracy of 99.3% to 99.5% [21]. However, the high accuracy is limited to separating PVC plastics from PET plastics, and is not applicable to other polymers [21], [49].

Infrared spectroscopy has proven popular as a means to identify plastics in both absorption and reflectance modes. Two infrared ranges, near infrared (NIR) and mid-infrared (MIR), have been used for plastics identification. Sommer reports the use of NIR spectroscopy for identifying five types of post-consumer plastics: PET, PVC, polyethylene (PE), polystyrene (PS), and polypropylene (PP) [49]. NIR spectroscopy capable of identifying plastics quickly allows online and inline identification [12], but it cannot identify dark colored plastics [21], [49].

MIR spectroscopy is able to distinguish a variety of plastics with close chemical structures regardless of their colors [17], [21]. However, due to its sensitivity to the surface state of the object identified, MIR spectroscopy cannot reliably identify plastics with different surface conditions.

Spaniol and Ehrle suggest infrared laser impulse thermography to identify 22 plastics based on their inherent thermal and optical properties [50]. In their approach, a high-energetic CO_2 laser beam heats the surface of the plastics to cause different maximum temperatures, temperature gradients, and heat distributions for different types of plastics. After a specific cooling time, infrared laser impulse thermography can identify engineering plastics regardless of their thickness, color, and aging.

Raman spectroscopy is a promising technique to reliably identify a wide rage of plastic types on the basis of their vibrational signatures. It features discriminative capability between neighbor plastics, and an identification time of less than one second for natural color plastics [1], [17], [21]. Unlike MIR spectroscopy, Raman spectroscopy is able to identify plastics with rough surfaces, plastic powders, and some mineral filler [17], [21]. In addition, it is insensitive to contaminants in plastics [49]. Kumar *et al.* report that Raman spectroscopy may be used to identify dark colored plastics if a low-power laser is used for a longer identification time [29].

Both forms of infrared spectroscopy and Raman spectroscopy require chemometric methods for classifying spectrochemical images. Recyclers endeavor to maintain a manageable number of distinct recovery streams in the face of the large variability that exists in plastic material formulation within type. Establishing identification boundaries under such circumstances presents a significant analysis challenge. Recent research has assembled very large sets of standard known electronic materials plastic samples from post-consumer and post-industrial sources in order to develop best practices and figures of merit for reliability of analysis [36].

All of the above technologies can be applied not only to identify disassembled plastic parts, but also to verify the purity of post-industrial or post-consumer plastic pieces. For example, NIR spectroscopy and Raman spectroscopy can be used to verify the quality of shredded post-consumer plastics. In Section II-C, we review mechanical plastic identification technologies for bulk processing.

C. *Mechanical Plastic Separation Technologies*

In mechanical separation for plastics-to-plastics recycling, contaminants are removed from plastic flows or mixed plastic flakes are separated into homogeneous resin streams. The success of the mechanical separation depends mainly on the physical properties of plastics, such as their density, surface free energy, surface roughness, or triboelectric charging property, and/or chemical structure. Mechanical plastic separation techniques include air classification, hydrocycloning, float-sink separation, froth-flotation separation, and electrostatic separation. In addition, magnetic and eddy current separations can be used to remove ferrous and nonferrous metal contaminants from plastic flows.

Air classification and hydrocycloning separate lighter particles from heavier ones by using air and water, respectively, as the fluid medium. The advantages of both methods include high throughput, low maintenance, and low operating costs. However, they depend for separation efficiency on the density difference of mixed particles and the uniformity of particle sizes [9], [55]. For example, the density difference between PVC and PET is too small for separation by air classification or hydrocycloning [45].

Super *et al.* present a float-sink separation method to separate thermoplastics from each other and from contaminants on the basis of their density difference [55]. This method separates mixed plastic particles in a sealed high-pressure chamber filled with near-critical CO_2 or near-critical mixtures of CO_2 and SF_6. When the chamber pressure is decreased, the highest density plastic particles sink first and are removed. The method can separate the mixtures of plastics which differ by a density of $3\ \mathrm{kg/m^3}$ regardless of loading and particle size.

Froth-flotation separation techniques utilize the hydrophobic and surface properties of plastics [45]. In froth-flotation separation processes, air bubbles in the liquid of an appropriate surface tension adhere and float plastic particles with a lower value of critical surface tension. Meanwhile, plastic particles with a higher value of critical surface tension are wetted sufficiently to suppress bubble attachment. The hydrophobicity of plastics can be modified by chemical or physical conditioning to improve the efficiency of the plastics flotation separation [45]. The surface chemical property, particle size, particle shape, and wetting agent significantly influence the efficiency of plastics flotation separation [46], [47].

In a different approach to plastics separation, electrostatic separation techniques utilize the difference in triboelectric properties of plastics [45]. Dodbiba *et al.* show that the efficient separation of acrylonitrile butadiene-styrene (ABS), PS, and PP significantly depends on tribocharging time, air inlet velocity, charging surface, air relative humidity and temperature, and electric field strength between electrodes [15]. Using a two-step triboelectrostatic process, the mixtures of ABS, PS, and PP formed in the laboratory can be separated into ABS, PS, and PP with a purity of 92.1%, 84.9% and 90.0%, respectively [15]. Wei and Realff compare several different processes of free-fall electrostatic separators under different distributions of the particle charges, feed rates, and product prices, and develop a simple guide for selecting an appropriate process [59].

TABLE II
SUMMARY OF PLASTICS RECYCLING PROCESSES FOR EOL ELECTRONICS PROPOSED IN THE LITERATURE

Study	Criteria	Recycling process design	Technologies used in process					
			Plastic pieces disassembled	Plastic piece handling	Plastics identification	Plastics sorting prior to shredding	Shredding	Separation after shredding
Arola et al. [3]	Plastic sales revenue and purity of recycled plastics	Manual whole-part sorting processes	✓	Manual	Identity labels or a spectroscopy instrument	Manual	NA	NA
		Automated whole-part sorting processes	✓	Conveyed	NIR spectroscopy	Automated	NA	NA
Krowinkel and Dalmijn [28]	Purity of recycled plastics	Bulk recycling process	NA	NA	NA	NA	✓	Magnetic, size, air shaking, wet shaking, eddy current, and electrostatic
Murphy et al. [34]	Relative cost and purity of recycled plastics	Plastics sorting process A	✓	Manual	Identity labels	Manual	✓	Mechanical
		Plastics sorting process B	✓	Manual	Spectroscopy for light plastics, and identity labels for black plastics	Manual	✓	Mechanical
		Plastics sorting process C	✓	Manual	Spectroscopy	Manual	✓	Mechanical
		Plastics sorting process D	✓	Conveyed	Spectroscopy for light plastics, and identity labels for black plastics	Manual	✓	Mechanical
		Plastics sorting process E	✓	Conveyed	Spectroscopy	Manual	✓	Mechanical
		Plastics sorting process F	✓	Manual	NA	Manual	✓	Mechanical
Rios et al. [42]	Staging space and material throughput	Typical bulk recycling process	NA	NA	NA	NA	✓	Magnetic
		Bulk recycling process combined with selective plastic disassembly and identification	✓	Conveyed	Raman spectroscopy	Manual	✓	Magnetic

*NA refers to "not applicable" for a particular process design.

Mechanical separation technologies preserve the plastic for closed-loop recycling. In Section II-D, chemical plastic separation techniques are discussed which convert plastics into alternative forms in open-loop recycling.

D. Chemical Plastic Separation Technologies

Chemical plastic recycling technologies convert plastic mixtures, which consist of different types of plastics and contaminants, into energy sources or monomers. Pyrolysis and gasification are examples of chemical plastic recycling technologies.

Pyrolysis decomposes mixed plastics into gas, oil, and residue at the temperature range of 600 °C–900 °C in the absence of oxygen [25], [26], [39]. Ramlow and Christill demonstrate that the composition and particle size of plastic input mixtures impact the composition of pyrolysis outputs. Due to their high calorific value and complex composition, the pyrolysis oil and gas are best used for heating, but unsuitable for use as a feedstock [39].

Koo and Kim present pyrolysis reaction kinetic models to predict the composition of gas, oil, and char from mixed PE and PS, given the input plastics composition, reaction time, and temperature [26]. Kiran *et al.* investigate the thermal degradation mechanism and kinetics of waste plastics using thermogravimetric curves [25].

Gasification converts plastics, including those that contain brominated flame-retardants, to gas at 700 °C. The generated gas is treated at higher than 1150 °C for about 2.5 s and then is rapidly cooled to approximately 50 °C. The results of gasification of ABS and HIPS containing polybrominated dibenzodioxins and dibenzofurans indicate that high temperature treatment and rapid cooling suppress the emission of brominated dioxins and furans to a very low level, and the synthetic gas can be used as a raw material in the chemical industry [61].

III. PROCESSES FOR RECYCLING PLASTICS FROM ELECTRONICS

Although technology is available for recycling plastics from EOL electronics, the electronic recycling industry is still determining how to efficiently and economically recover plastics from EOL electronics. The major challenges to plastics recycling from electronics are inefficiency of recycling operations, inconsistent properties and unreliable yields of recycled resins, low prices for virgin resins, and lack of demand for recycled resins [4], [14], [34], [38]. In this Section, we review plastics recycling processes and the development of plastics recycling networks for EOL electronics.

A. Design and Evaluation of Plastics Recycling Process for EOL Electronics

A comparison and evaluation of the plastics recycling processes reported in the literature are summarized in Table II. Arola *et al.* evaluate the economics and output plastics quality of both automated and manual whole-part sorting processes [3]. High-speed automated plastics identification technology is compared to laborers sorting plastics using plastic identity labels on parts or spectrometer identification. Unfortunately, due to coatings, pigments, a variety of contaminants, parts containing multiple plastics, unusual part geometries, and erroneous plastics identity labels, neither process attained a high purity level in which plastic sales offset capital and labor costs. The appropriate levels of manual and mechanical sorting depend on both the composition of incoming EOL electronics and the capability of recyclers [4].

Krowinkel and Dalmijn evaluate the separation process of shredded EOL televisions using mechanical recycling techniques without prior disassembly. Their process includes magnetic separation, size separation, air shaking separation, wet shaking separation, eddy current separation, and electrostatic separation. Their results demonstrate that the high levels of contaminants in the plastic materials recovered by the bulk process lowers the resale price [28].

Murphy *et al.* compare the costs of six different processes for identifying and sorting plastic flakes from EOL electronics. Out of the six processes evaluated, the two which use a conveyer and spectrographic identification for both natural and dark plastics have lower processing costs than the other processes. Meanwhile, the two processes which include spectrographic identification result in higher purity of output plastics [34].

Using discrete-event simulation, Rios *et al.* compare and evaluate a typical bulk recycling process versus their proposed process with selective plastic part disassembly and identification by Raman spectroscopy [42]. The performance of each of the two processes is evaluated according to the staging space needed, material throughputs, costs, and revenues. Their simulation results indicate that the selective disassembly of plastic parts does not produce a bottleneck, but rather, a balanced disassembly operation adds capacity to increase product turnover in the staging area and reduce the staging space needed. Furthermore, the selective disassembly, plastics identification, and sorting do not interfere with metals throughput, but rather simply add output streams of high-value engineering plastics. The capital and labor costs of selective disassembly and plastics identification are offset by the high value of recovered engineering plastics and staging space savings. Therefore, the proposed process offers both environmental and economic benefits.

B. Developing Plastics Recycling Networks

The forward and reverse supply chain for engineering thermoplastics includes resin suppliers, compounders, molders, electronics manufacturers, electronics recyclers, plastics processors, and end users. An analysis by Dillon reveals that the major issues in recovering engineering plastics from electronics are the lack of a consistent quality supply and insufficient demand for recycled engineering thermoplastics [14]. Pohlen and Farris identify the structure of the reverse logistics channels for post-industrial and post-consumer plastics, the entities and functions of the reverse channels, and factors affecting reverse logistics flows [38]. The reverse logistics channels include municipal pickup, material recovery facilities, plastics processors, and manufacturers, and perform the collection, sorting, storage, transport, shredding, densification, processing/filtration, and demanufacturing functions.

The optimization of the reverse supply chain for electronics recycling is explored without a specific focus on plastics recovery in [22], [35], and [48]. Murphy *et al.*, on the other hand, develop a model to evaluate and compare entities in thermoplastics recycling networks with different processing sequences and/or technologies in order to identify tradeoffs, key cost drivers, and sourcing options [34]. Yoshinaga *et al.* combine the Geographical Information System with simulation of inverse logistics to evaluate a plastics recycling network in Japan [62].

IV. PRACTICES FOR RECYCLING PLASTICS FROM ELECTRONICS

Plastics recycled from electronics find uses that range from the conversion of mixed plastics for lumber to the separation of pure plastics for closed-loop recycling. In this Section, we review successful plastics recycling practices.

Plastic lumber manufactured using post-consumer plastics can be used in a variety of construction applications, and possess beneficial properties such as durability and resistance to rot for marine construction. For example, evaluation of TRIMAX plastic lumber in a fixed pier in Old Field, NY, over a two-year exposure period shows consistent hardness and dimensional stability but increased compression modulus and bleeding modulus [11].

An engineering plastics processor and research facility, MBA Polymer, Inc., has demonstrated how the quality requirements of recycled plastics for high-end applications can be met given real-world recycling conditions and has developed an assay model to determine the prices of the incoming plastic scrap [4]. In January 2004, MBA Polymer, Inc. and Guangzhou Iron and Steel Enterprises Holdings, Ltd. formed a joint venture to build and operate a state-of-the-art commercial plastics recycling facility in Guangzhou, China [2].

BASF AG, Ludwigshafen, and the German Association of the Electrotechnical Industry (ZVEI) jointly conducted a project to recover plastics from EOL electric and electronic equipment in a pilot plant of Berlin Consult [39]. In the project, the mixed plastics with contaminants are recovered into pyrolysis gas, oil, and residue using the Pyrocom process, which combines pyrolysis with combustion.

Concurrent Technologies Corporation has developed libraries for Raman spectroscopic analysis and sorting of post-consumer electronic plastic waste materials [56]. Their analysis approach is capable of identifying a variety of polymers in less than one second with no requirement to preclean and precisely position plastic pieces for identification. The rapid identification and easy operation of the system seeks to offset labor costs of plastics recycling processes with increased purity of recycled plastics.

In addition, the workgroup, AG CYCLE, brings together major plastic manufacturers, plastic compounding operations and recyclers to cooperate on new technology for plastics life cycle management. One of their collaborative projects was to develop labels that are fully compatible with recycling ABS, PC, and HIPS parts [54].

V. ANALYSIS AND CONCLUSION

Challenging the implementation of plastics recovery processes is the wide variety of product sizes, shapes, fasteners, types of plastics, and types of additives to plastics. Therefore, more research efforts need to be directed toward overcoming implementation issues. In the future, product design standards may reduce separation difficulties. For example, at the product design and manufacturing stages, selection and marking of renewable materials and more easily-recycled materials may improve the future separation of materials at the product end-of-life stage. Likewise, design for materials separation may reduce the time, equipment requirements, and costs associated with demanufacturing for materials recovery. Furthermore, improved product information systems may provide product structure and materials information to reduce disassembly and identification time and cost. Information links between reverse supply chain entities that include electronics recyclers, plastics processors, compounders, and molders, would improve recycled plastic flows. To develop recycled plastics markets, consistently high quantities of plastics must be separated at certified purity levels.

Plastics used in business and consumer electronic equipment have to meet international fire performance requirements and additional requirements from the regulations of different countries [33]. The various requirements result in different amounts and types of flame-retardants added into plastics used in electronic equipment. Identification and separation of plastics contaminated with various flame retardants complicate the development of a flow of post-consumer plastics from electronics recyclers to blenders [7]. Spectral library designs and hierarchal classification strategies are needed to recognize contaminating additives in streams in which base resins present variable signatures. For effectiveness under real-world regulatory conditions, it is important to extend recycling process design and scheduling management tools to separate plastics not only by type but also by natural or dark color group and flame-retardant additive, with an eye toward European legislations [16]. Future sortation by three additive categories is needed: brominated flame retardant, other flame retardant, and no-flame-retardant additive. In addition, future research is needed to separate plastics not only by type and color but also by flame-retardant additive since incineration of contaminant plastics must be monitored for dioxin emissions from plastics with flame retardants [24]. Prior identification and removal of plastics with the brominated flame retardants could reduce the probability of hazardous emissions.

In this paper, we reviewed research for recycling plastics from EOL electronics. We discussed the technologies for separation and identification. Recycling process designs were compared, and plastics recycling network models were reviewed. Several successful plastics recycling practices have demonstrated the potential for economically viable plastics recycling. Effective technologies to separate and identify plastics can enhance the value of the output streams from electronics recycling. Future supply chain requirements were discussed.

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Xiuli Qu received the B.S.E.E. and M.S.E.E. degrees from the University of Science and Technology Beijing, Beijing, China, and the M.S.I.E. degree from Purdue University, West Lafayette, IN, where she is currently pursuing the Ph.D. degree in industrial engineering.

Her current research focuses on modeling reverse supply chains and appointment scheduling in the healthcare industry.

Ms. Qu is a member of INFORMS and IIE.

Julie Ann Stuart Williams received the Ph.D. degree from the Georgia Institute of Technology, Atlanta.

She is an Associate Professor in the Department of Management and MIS at the University of West Florida, Pensacola. She previously served on the faculty at Purdue University, West Lafayette, IN, and The Ohio State University, Columbus. Her research and teaching interests focus on sustainable systems and healthcare engineering.

Prof. Williams is a Registered Professional Engineer in the state of Ohio and is a member of INFORMS and ISIE.

Edward R. Grant received the Ph.D. degree as an NDEA Title IV Fellow at the University of California, Davis.

He is a Professor and Head of Chemistry at the University of British Columbia (UBC), Vancouver, BC, Canada. He worked on the theory of unimolecular reaction dynamics as a National Science Foundation Postdoctoral Fellow at the University of California, Irvine, and proceeded to experimental studies of laser-crossed molecular beam reactive scattering at the University of California, Berkeley. He has held the ranks of Assistant and Associate Professor of Chemistry at Cornell University, Ithaca, NY, and Professor of Chemistry at Purdue University, West Lafayette, IN, prior to joining the faculty at UBC in 2005.