PART 1

TROUBLESHOOTING BASICS
The Economics of Troubleshooting Polymer Processing Systems

Mark D. Wetzel
E. I. du Pont de Nemours and Company
Engineering Research and Technology
Wilmington, Delaware, USA

Abstract
Polymer processing is a very cost competitive, but capital intensive endeavor. Most industrial operations consist of a sequence of complex mechanical, electric and thermal components, where ingredients are combined or transformed into higher value products to be sold to customers in the market. The equipment can experience problems that can negatively impact productivity and quality. Proper investments are required in expertise, hardware and software to enable a manufacturing organization to troubleshoot and resolve these problems in order for the business to remain viable in the global marketplace. This chapter examines the economics of key aspects of polymer processing troubleshooting in order to assist the reader in making decisions about how to plan for and make strategic investments in technology and expertise in order to maintain and optimize equipment performance and manufacturing productivity.

Keywords: Extrusion, compounding, economics, troubleshooting, uptime, yield, cost, safety, productivity, facilities, equipment, process, measurement, analysis

1.1 Introduction

The industrial practice of polymer processing has become very cost competitive while requiring a capital intensive set of operations that includes synthesis (polymerization), chemical modification, compounding, and forming or shaping steps. Most systems consist of a sequence of complex mechanical, electric and thermal components, where ingredients are combined or transformed into higher value products to be sold to customers in the market. In order to establish, grow or maintain a profitable business, manufacturing assets must operate at or near peak performance levels that deliver products with consistent properties and high quality. However, polymer processing equipment does experience many problems that can negatively impact productivity and quality. Proper investments are required in expertise, hardware and software to enable a manufacturing organization to troubleshoot and resolve these problems in order for the business to remain viable in the global marketplace.

This chapter examines the economics of polymer processing troubleshooting to assist the reader in making decisions about how to plan for and make strategic investments in
technology and expertise in order to maintain and optimize equipment performance and manufacturing productivity. Another objective is to show how it could cost more money or put a business at risk by avoiding the proper commitment to the resources required to identify the causes of processing problems and resolve them in a timely and economically viable way.

1.2 Economic Incentives and Necessities

Competitive industries like plastics processing demand high productivity in order to be profitable. Capital intensive manufacturing operations require high asset utilization. Key metrics can be used to quantify system economic performance and justify or track the costs of troubleshooting investments. The following measures are useful in determining the financial contribution of a process or set of resources allocated to that operation.

1. Uptime can be defined as the time that an asset is used to make a product that can be sold, divided by the time that the asset is available to run:

\[
\% Uptime = \frac{t_{\text{Run}}}{t_{\text{Available}}} \times 100
\]  

(1.1)

The time available can include or exclude a number of normal production events. For example, annual plant shutdowns or routine, scheduled equipment overhauls may be excluded from the calculation. It is important that the uptime calculation be consistent over long times, so that performance changes can be compared with benchmarks. Depending on the process, uptime can range from 50 to over 95 percent. For example, a continuous polymerization unit can operate at uptimes from 90–95 percent. A small-lots custom compounding line may have an uptime of 50 to 65 percent. Catastrophic equipment problems, such as extruder screw and shaft breakage or motor drive failures have a serious impact on uptime. Material feed bridging, die hole freeze-off, die drips and plugged vacuum ports are examples of operational problems that also affect uptime.

2. Yield is the material produced that can be sold, divided by the total material processed. First-pass yield is the material that can be sold as a premium product meeting all specifications, divided by the total processed. Product that can be sold as second-grade or scrap may provide income, but first-pass yield is the goal-setting standard. Processes that are unstable or experience frequent upsets can produce significant off-spec products, adversely impacting yield. Uptime and yield are the two most common metrics used to assess manufacturing line productivity.

3. Customer satisfaction and demand is the most important measure of a product’s market value and viability. Poor quality can put a company out of business. Failure to meet demand could constrain growth and prompt a competitor to invest in a new asset to make the same or similar products that take market share.

4. Labor cost includes all resources allocated to a production line. This includes operators, engineers, chemists, mechanics and other skilled trades, contractors,
consultants, quality control or analytical laboratory staff, management and other overhead. Processes with frequent equipment failures can experience high labor costs.

5. **Energy cost** can be used to measure process efficiency. An extrusion line with poor temperature control may cost more to operate than one equipped with a modern computer system and well-tuned closed-loop controllers.

6. **Auxiliary or support equipment** includes the hardware or systems required to maintain process operations. Computers, software, instrumentation and testing tools may be needed in order to diagnose and resolve problems or prevent upsets or failure that impact uptime and yield.

7. **Waste generation and disposal** is another economic indicator of asset productivity and sustainability. Processes with frequent upsets or equipment problems can generate more waste that incurs a disposal and potential environmental cost. Excessive edge trim in a film line could increase the waste or material used as "re-work."

8. **Safety, health and environmental** events and impacts can be related to process problems and equipment failures. The cost of safety and environmental incidents or near misses can be tracked and correlated to process performance metrics, including uptime and yield. The failure to diagnose and resolve a process problem quickly could result in a serious injury or environmental release that could shut a line down for an indefinite period with potential legal consequences, not to mention the pain and suffering caused to individuals, families or the community.

9. **Capital productivity** can be calculated using uptime or yield data and the known fixed capital investment and depreciation costs. One may also include labor, energy and feedstock costs.

10. **Process capability** is a measure of how well an operation performs under the best conditions. It establishes valid uptime, yield and cost metrics to be compared over time. As problems arise, uptime, yield and costs will change and can be tracked over short and long time periods.

11. **Financial metrics and conventional accounting methods** can be applied to quantify manufacturing performance by combining sales or income with operating costs. Calculations that can be used include RONA (Return on Net Assets), ROI (Return on Investment) and other standard accounting practices that are used to manage costs and determine profitability. These methods will reflect the impact troubleshooting investments have on sales and costs.

These and other measures represent "hard" numbers that quantify process performance from a cost and benefit perspective. While minimizing production cost is critical in a competitive environment, uptime, yield and customer satisfaction ultimately determine if a company will thrive. In order to determine the investment needed for troubleshooting and its impact to the business, benchmark productivity values must be established. Uptime, yield and other baseline values can be estimated based on a manufacturing line's current or past performance. Daily, weekly or monthly calculations can be used to track short term trends, while quarterly or yearly measures may be used to quantify long term behavior. For some systems, short-term production throughput may be recorded and tracked (pounds/hour, parts/hour, feet/minute, rejects/hour and the like). Dynamic fluctuations and
running averages may be useful in identifying process problems and gauging the impact of troubleshooting efforts. Economic metrics can be normalized to account for changes in labor, materials, energy and other variable costs. Standard financial and statistical methods can be applied to analyze and compare long and short term performance estimates as compared to the baseline. These data can be used to establish a benchmark level, or to create measurable goals for an operation to strive for.

1.3 Troubleshooting Resources and Their Cost

A proper investment in troubleshooting expertise and equipment should be made in order to maintain a process operation at its designed capacity and benchmark uptime or first-pass yield, while minimizing the contributors to costs as outlined above. While troubleshooting infrastructure (expertise, hardware and software) can incur a significant cost to a business, it can easily pay for itself by solving problems quickly that might otherwise result in a catastrophic failure. State-of-the-art process equipment from established suppliers is usually equipped with sensors, electronic hardware and control system and diagnostic software that are critical tools for troubleshooting activities. Older manufacturing lines should be considered for replacement or upgrading with the latest diagnostic capabilities. The technical components of a typical extrusion compounding line will be used to exemplify how required expertise and capabilities can be identified.

1. Feedstock materials and additives (inputs). Reputable suppliers provide materials that consistently meet technical specifications. However, there are occasions where an off-spec lot of material may be delivered to a compounding plant. Furthermore, the supplier may change their process or their own sourcing, so that the material properties change slightly, but still meet product specifications. Your own formulation may change or replace one component with a material from a different supplier. Small changes in ingredients or formulation could result in problems that affect product quality, yield or process uptime. For example, two different high density polyethylene (HDPE) feed stocks may have the same melt flow index, but their molecular weight distributions may differ. A simple HDPE substitution could result in poor compounding performance as indicated by torque and pressure oscillations that could affect the time-temperature-stress history experienced by the formulation resulting in product property variability. Furthermore, customers might experience process upsets resulting in poor film quality or excess flash or mold deposit in injection molded parts. Thus, sufficient knowledge of polymers, additives and their interactions is required in order to diagnose material-related problems. Material suppliers may provide some information and expertise, but they do not know about your proprietary formulations and processing systems. Thus, sufficient expertise and infrastructure are needed in the fields of polymer chemistry and processing. A large company can support in-house expertise that can be leveraged across business units and product types. A toll manufacturer may know their technology, but they may require contract partners (suppliers, consultants, and engineering firms) to provide expertise for the materials used and the process methodology employed.
2. **Product properties, quality, release and application support (outputs).** It is assumed that a company has developed expertise, analytical tools and customer service resources to qualify products for release, assist customers in end-use application development, and diagnose problems as they arise. Troubleshooting a process may require expertise and analytical capabilities that measure product properties beyond normal release testing, or involve additional resources when investigating a customer complaint. For example, polymer blends that involve interfacial grafting reactions may conform to release specifications as measured by tensile properties and IZOD impact resistance. A compounding process problem that results in insufficient mixing and grafting can cause a change in dispersed phase droplet size and interfacial adhesion. This may not be detected in standard release tests, but could appear over time as a mold deposit problem in a customer's injection molding system. Thus, technical expertise in polymer blend processing and structure-property relationships, and injection molding technology must be available to identify the root cause of the problem in the compounding line or input feed stocks.

3. **Buildings and infrastructure.** Plant site location, building design, equipment location, electrical power, water (quantity and quality), environmental control (temperature, humidity, air quality and other factors) and other basic services can impact production and product quality. Plant and industrial engineering or safety, health and environmental expertise may be needed to diagnose process problems. For example, processes using polyamides and polyesters may be very sensitive to ambient humidity when drying systems are not employed. In this case, expertise in polymer chemistry and processing are needed, along with building services personnel, to provide humidity measurements or control. Unreliable or highly variable electric power sources can cause intermittent process upsets or induce product variations. Improper power and sensor wiring or grounding could also manifest into process problems that are very difficult to diagnose. Plant and power engineers, electricians and instrumentation technicians are needed to resolve such problems. Water quality can negatively impact product quality or equipment. For example, if hard water is not properly treated and is used for cooling extruder barrels, small channels can become clogged and prevent effective temperature control.

4. **Mechanical and thermal equipment.** A typical compounding process consists of many complex mechanical and thermal components or subsystems. These include material handling and transport, drying, feeding and metering, extruders, quench baths, cutters and bagging systems. Each component requires specialized expertise in materials of construction, fundamentals of wear, fatigue or failure, mechanical systems design, heat transfer, rotating machinery and the like. For example, film gage thickness variation could be caused by excessive or eccentric roll wear, bearing failure, gear chattering, temperature variations on chill rolls, or flow instabilities in an extruder or die. Mechanics and mechanical engineers are needed to service these systems.
5. **Electrical equipment.** Extrusion systems utilize many electrical components to provide mechanical motion and thermal energy (heating and cooling). Troubleshooting electrical components may begin with the power source, be it purchased from a utility or generated on-site. Problems may arise with transformers, switches, breakers or wiring. Polymer processing lines may utilize complex configurations of motors, drives, switches, fuses and extensive wire runs and connections. Licensed electricians may be needed for installation and modifications of electrical components. Electricians and electrical engineers may be needed to diagnose and resolve problems to these components and subsystems.

6. **Sensors and measurement technology.** Modern polymer processing units utilize many sensors and on-line monitoring systems. Temperature and pressure measurements are critical for maintaining process operations and safety. Sophisticated measurement technology may be used for product release or real-time product property control. For example, film gage thickness scanners require highly-trained technical support personnel in order to set-up, operate, diagnose problems and make repairs.

7. **Control systems, computers and support software.** Personal computers (PCs), programmable logic controllers (PLCs), embedded controllers and instrumentation/control systems are ubiquitous in the plastics industry. Control engineers, information technology resources and software specialists are needed to manage PCs, networks, software packages and security. Simple, but serious problems, such as setting or maintaining PID (Proportional + Integral + Derivative) control loop tuning or auto-tuning procedure management may require access to control engineering expertise. In some instances, changes in feedstock materials, mechanical, thermal or electrical equipment alterations and service, or sensor and instrumentation replacement or repair could cause problems for data monitoring and control systems. Thus, multidisciplinary resources may be needed to troubleshoot sophisticated, automated manufacturing lines.

8. **Process operations.** Skilled and experienced operators and technicians are the first line of defense in diagnosing and resolving problems on a polymer processing line. Routine or recurring events or failures can be examined and corrected by the operations team. Many companies dedicate engineers to a manufacturing operation to provide the next level of expertise to perform troubleshooting functions, improve uptime and yield or commercialize new products. While a highly skilled, experienced and motivated operations team may represent a significant cost, the return on investment can be justified and quantified by the financial metrics described previously (most notably, uptime and yield).

9. **Operations management.** Process problems can have a significant impact on uptime, yield and customer satisfaction. Product shipments may be delayed or orders may go unfulfilled if yields drop below the demand level. Product scheduling “wheels” may be impacted and changes could cause other problems. The operations management team must make critical decisions in resource allocation and expenditures for troubleshooting activities and the efforts needed to recover to normal conditions. For example, a line supervisor may need to make
the decision to shut a line down, engage internal or external expertise, and then develop plans and manage the tasks for resuming production, adjusting schedules and product delivery.

10. **Unit operations fundamentals.** Difficult or seemingly intractable problems may require specialized expertise in chemistry, chemical engineering, fluid mechanics, metallurgy or other domains. For example, extrusion compounding process development, commercialization and problem diagnosis may require a fundamental understanding of "unit operations" that include polymer melting, polymer, filler or additives mixing, chemical reaction kinetics, devolatilization, polymer degradation, polymer flow through a die, quenching and crystallization kinetics.

The costs for these resources depend on the level of expertise, experience and geographic location. A highly-skilled workforce requires additional investment in training and education. Personnel possessing experience with sophisticated and complex technologies should not be underestimated, even though they are likely to cost more than inexperienced staff. Skilled and experienced practitioners usually diagnose and resolve difficult problems far more quickly than inexperienced or unskilled operators and engineers. While emerging regions may offer a low wage structure, one must determine if the required skills are available locally or must be imported from developed economies. Furthermore, many companies manufacturing in emerging economies suffer from employee retention problems. That is, the investment in training and the experience gained at your company may be lost to a competitor offering a higher wage or salary. A cost-benefit analysis is needed to determine what level of expertise is required in order to achieve or maintain uptime, yield and customer satisfaction objectives. Commodity product manufacturers focus on cost and productivity to drive margins and competitiveness, while specialty producers may rely on manufacturing flexibility and sophistication to tailor high-value product properties. Each strategy can afford different levels of resourcing for troubleshooting activities as a part of the overall manufacturing operation cost.

A manufacturing operations organization may first identify what resources are required to meet production goals. Next, those resources may be hired directly, created through internal training, or contracted externally. Cost and other constraints (for example, plant location) will guide the decision to establish internal capabilities or engage external resources. Polymer processing systems have grown in complexity and capability as diverse technologies have evolved integrating mechanical, electrical, sensing and controls functions [1]. Likewise, troubleshooting requires complementary expertise that may be found in-house or outside your company. The following are examples of resources organized by functional groups found in the plastics and allied industries.

1. **Manufacturing.** As discussed above, the manufacturing organization provides the first line of defense in problem diagnosis and resolution. A process cannot run without operators, line engineers and supporting functions (mechanics, electricians, and others).

2. **Analytical testing laboratories.** Product release, quality control and problem resolution depend on careful physical property measurements and their interpretation. The analytical function offers expertise and individuals trained to
operate specific equipment and perform standard test methods. For example, rheological characterization of polymers with capillary or parallel plate rheometers has proven to play a critical role in diagnosing difficult problems caused by feed stock materials or process induced changes.

3. **Research and development (R&D).** The R&D organization may possess specialized expertise in chemistry, chemical engineering or polymer processing. Material science or process fundamentals may also be found at certain academic institutions or government laboratories. These resources are most valuable when trying to resolve very difficult process problems or situations that involve different science and engineering domains.

4. **Engineering services.** Many companies have leveraged engineering services groups in-house or contract outside firms for process design and construction. Expertise may be found from a variety of sources in mechanical engineering, metallurgy (material selection or failure analysis), electrical power systems and other fields.

5. **Equipment manufacturers.** Equipment and component suppliers possess deep knowledge and can provide critical resources for troubleshooting a polymer process. Vendors usually have a technical support organization and may tap into their R&D groups to help customers resolve problems. They know their equipment, but they may not know your process or materials. While a complex turn-key system is supplied by one company, it consists of many components purchased from many other suppliers. A supplier support network must be established so that the right resources can be engaged in a troubleshooting event. Equipment manufacturers should also provide detailed information in their manuals to aid in troubleshooting.

6. **Material suppliers.** Polymer, filler and additives suppliers provide information and technical support for their products. Like equipment manufacturers, material suppliers can provide resources that are critical in the resolution of process problems.

7. **Customer service.** Many companies provide technical support to customers for product application development. Sales and marketing organizations frequently interact with customers to resolve technical issues. Many times, the problems that customers experience with products migrate from these organizations to the manufacturing organization. These groups may have expertise or facilities with technologies used by customers that can be used in troubleshooting activities. Your technical service laboratory may perform end use testing to help diagnose and resolve a problem in the plant.

8. **Customers.** Product quality problems may be first noticed by customers. A long-term supplier-customer relationship can facilitate the engagement of additional resources to help you diagnose and resolve a problem. A good customer may offer laboratory facilities and expertise to help you restore or improve product quality.

9. **Consultants.** Individuals or consulting firms provide specific expertise on an as-needed basis. Some manufacturers have an in-house leveraged consulting organization. Many academics consult with industry.

10. **Contractors.** Individual contractors or contract services companies provide expertise and resources that can be engaged in troubleshooting activities.
Outsourced electricians, mechanics and other crafts may be engaged on an as-needed basis.

11. **Professional societies and networks.** Organizations, such as the Society of Plastics Engineers, provide contacts, technical information and training materials to the industry. Conferences and active members of a professional organization provide opportunities to gain know-how and form personal networks with consultants, equipment manufacturers, material suppliers and peers faced with similar process problems and issues. Individual practitioners who actively participate in professional societies will gain direct access to experts and knowledge that will make a significant impact on problem diagnosis and resolution.

12. **Textbooks, papers, troubleshooting guides, and on-line resources.** You purchased this book for guidance on process troubleshooting. Texts, journal publications, magazine articles and on-line content provide a wealth of information that is essential to aid in troubleshooting activities. Just one piece of information from a book that helps solve a problem can easily justify the purchase of technical information. While much useful information is available on the Internet for no cost, it is usually incomplete and not necessarily reviewed for accuracy (i.e., you get what you pay for).

13. **Training resources.** Consultants, professional societies, universities and equipment/material suppliers may offer training that will help operators, engineers and support functions gain expertise in troubleshooting methods, problem diagnosis and resolution. Whom do you call or where do you turn when you need to diagnose or solve a problem? From an economic perspective, the time value of money is a key driver for making investments in troubleshooting resources before a serious problem occurs. Continuing education and internal/external networking with experts and other resources are important parts of a practitioner's work, career development and economic value to an organization.

### 1.4 Managing Resources and Costs

After a manufacturing organization has determined what technical resources are needed to troubleshoot a process, and how and when these resources are to be engaged, their costs must be managed. Decisions must be made on whether resources needed for troubleshooting utilize employees and to what extent and how to engage external consultants or other companies. Furthermore, training, employee career development and advancement must be managed in order to retain operators, technicians, engineers and managers as they gain know-how and experience. Depending on the industry segment, cost constraints may force managers to outsource resources or off-shore manufacturing facilities. A careful cost-benefit analysis is required to determine which functions should be established or retained in-house.

Uptime, yield and customer satisfaction are very time-sensitive measures of process output. The time it takes to diagnose and resolve a process problem depends on how quickly the right resources are engaged and for how long. External resources need to know intimate details of your process, including proprietary information, in order to be effective in a timely manner. Thus, there are risks that outsourcing or off-shoring troubleshooting
resources could extend the time to implement a solution or leak sensitive information to competitors.

Efficient internal and external resource management is critical for timely problem identification, diagnosis and resolution. Individuals, including operators, engineers and managers, must establish and maintain a personal network, or a "whom do I call" list. It is important to establish long-term relationships with service providers, including internal resources, consultants, equipment manufacturers and contractors. Unless a problem is very common or a process is simple, one should not expect to call a consultant in and obtain a solution in one visit. It takes a significant time investment by both parties for information exchange and process testing to determine the cause of a problem or diagnose an equipment failure.

External resources can be paid through service contracts or on a time and materials basis ("pay as you go"). A cost versus time decision must be made on how to manage these resources. Usually, service contracts are more expensive, but they guarantee a rapid response time for hardware delivery and engagement from technical support personnel. This decision must also consider the reputation and track record of the service provider. Equipment supplier reliability and durability should also be included in the cost calculations and resourcing decisions.

1.5 Troubleshooting Techniques and Their Relative Costs

In this section, typical troubleshooting approaches and their relative costs in resources and equipment are examined. Modern polymer processing lines usually include basic instrumentation and control system components that provide information critical to operations, including temperatures, pressures and motor power (or amperage, percent torque and other indicators). A manufacturing control system also possesses hardware or software to prevent catastrophic equipment failure or damage by preventing excursions above operating limits, such as screw shaft torque, die pressure, barrel or polymer temperatures. System shutdown and alarms can be useful in diagnosing problems that interrupt production. Many processes include computer-based supervisory control and monitoring systems that record and manage discrete actions (valve switching, motor actuation, alarms and shutdowns). These systems may also record and display continuous measurements, such as temperatures using thermocouples (TCs) or resistive temperature devices (RTDs), melt pressure, motor power, and other inputs. Conventional data acquisition and control systems may update, display or store these measurements at sample rates from one sample per second (control and display) to one sample per minute (archival). For troubleshooting activities, an investment in making critical measurements and utilizing computer-based control and monitoring system can be essential. Additional resources are required to develop and maintain sensors, signal conditioning hardware, control system hardware and software. Operators and line engineers require training and must gain experience in making effective use of this technology for troubleshooting activities.

1. Process capability assessment and variability. Assuming that a production line is equipped with standard measurements and a control and monitoring system, a "product by process" approach can be adopted to establish an operational baseline and process capability described previously. Basic statistical methods
(statistical process control, SPC) may be applied to determine short and long-term average values and the variability (variance or standard deviation) for each measured value and alarm state. Operators and line engineers need to invest time in adopting or developing the data retrieval, analysis and reporting methods in order to detect process problems and determine a root cause. “Product by process” troubleshooting requires that measurement sensitivity and dynamic response are sufficient to detect a problem and determine the root cause from a large number of possible sources. Conventional measurements and control systems may not provide all of the information needed to detect and diagnose a process-induced or feedstock material problem.

2. **On-line, at-line and off-line measurements.** Additional investments in sensors and measurement systems may be necessary to support troubleshooting activities. Material characterization by an analytical laboratory may be used for product release or problem solving. Analytical costs and the training of and time spent by operators or line engineers in obtaining and interpreting these analyses must be budgeted for. The addition of sensors or material measurement systems can incur significant hardware, software, installation and maintenance costs. While these auxiliary investments may not be necessary for production and product release, they can be very valuable for problem diagnosis [2]. Additional quantitative information, even if redundant, usually hastens the task of sorting out and determining the root cause of a problem from many possibilities or complex interactions.

3. **Process perturbation methods and analysis.** Most process control systems record and display information at sample rates from one value per second to one value per minute. This represents the “steady-state” condition or slow time varying dynamics. Troubleshooting functions can be augmented by measuring transient, oscillatory or chaotic events using high-speed data acquisition and analysis hardware and software [2]. Usually, conventional Programmable Logic Controller (PLC) or Personal Computer (PC) based control and monitoring systems are not designed to acquire and analyze dynamic signals at sample rates from 10 Hz to 10 kHz. An additional investment may be required in procuring or building, and then utilizing a dynamic monitoring tool. External resources (research and development, consultants or engineering services) can be engaged to bring equipment to a plant, set up and run dynamic monitoring tests. Specialized perturbation experiments can be conducted to induce a dynamic process response to assist in troubleshooting diagnosis.

4. **Pilot lines and laboratory facilities.** While considered a luxury in many commodity businesses, small-scale or pilot polymer processing systems have proven invaluable in diagnosing and resolving problems on manufacturing lines. These systems can be used to emulate critical unit operations in a manufacturing process in a controlled and well-instrumented environment, while consuming small amounts of materials. If the problem can be reproduced at the lab-scale, key variables and operating conditions can be identified and quantified. Once the problem source is identified, then the lab system can be used to find or demonstrate the solution that can then be scaled up to the plant process. This technique is most valuable when troubleshooting seemingly intractable problems or situations where plant control systems and instrumentation cannot
measure critical variables related to the problem. However, pilot and lab-scale polymer processing systems represent a large capital and resource intensive investment. Highly-trained specialists are required to make effective and lever-aged use of the equipment.

1.6 Case Histories

Several examples are presented that describe troubleshooting activities utilizing different investment levels in expertise and equipment.

1.6.1 Single Screw Extrusion Instability

A large polyolefin single screw extrusion line was suddenly experiencing flow instabilities and bridging in the feed hopper after many years of production. Skilled, experienced operators discovered the oscillation from control system motor power and melt pressure traces that exceeded control limits. They temporarily solved the problem by reducing the screw speed which lowered throughput resulting in a loss in first pass yield, an economically unacceptable situation. Operations management engaged a process engineer to investigate. The engineer reproduced the problem by increasing the screw speed and found bridging in the feed hopper. By following a classical root-cause analysis, changes in the feedstock polymer size, shape and friction coefficient were rejected. Screw wear was suspected, but a regular process shutdown for maintenance was not scheduled for several months. Extrusion experts were called in to assist the line engineer to determine plausible causes and design a strategy to complete the diagnosis and resolve the situation. While barrel, barrel groove or screw wear in the feed and melting section were plausible causes, other possibilities were explored that did not require a line shutdown. A thermal imaging camera was obtained in order to measure the temperature distribution in the feed throat and along the steam-heated extruder barrel. The barrel insulation was removed and thermal images shown in Figure 1.1 were captured showing large temperature non-uniformities in the melting zone. Hot and cold spots were identified in the solid transport and transition region that were determined to be most likely to cause melting zone instability near the feed throat that resulted in bridging and surging behavior at the discharge. Further investigation showed that corrosion in the steam heating lines caused uneven heating around the barrel resulting in hot and cold regions. Thus, variations in solid transport behavior (polymer-barrel friction) and melt film formation from heat transfer with the barrel surface induced the instability. Ultimately, the barrel section was replaced and the process was restored to a stable condition at the target throughput and benchmark yield. In this case, the cost to production was in yield loss and the resources required diagnosing and solving the problem (operators, engineers and consultants).

1.6.2 Compounding Extruder Catastrophic Failure

A polyamide compounding extruder suffered from an intermittent, catastrophic hardware failure where a screw flight in the melting zone would break and then cause damage to downstream screw elements and barrel liners. The resulting failure caused a shutdown that lasted up to one week for repairs, impacting the uptime significantly. Operators and
line engineers in the control room noticed a periodic dropout in the extruder motor power signal. The engineer suspected that the dropout was indicative of a drive system problem that may have resulted in a cyclic fatigue failure of the screw element in response to transient stresses in the melting section. A metallurgist was engaged to examine the broken screw element. It was found that the element was hardened for wear resistance, making it more brittle. It could not be determined if cyclic fatigue alone caused the failure. The cause of the load transient could not be determined with the data from the conventional control system or from plant experience. Extrusion experts were called in to find the root cause.

The compounding process control system was not designed to capture or analyze transient event data. A specialized high-speed data acquisition system and a novel process perturbation method, the “Pulse Technique,” were employed to diagnose the cause of the extruder motor power dropouts [3–7]. Data captured at sample rates from 60 to 200 Hz showed that the periodic dropouts were actually negative transient spikes in power followed by a large increase and decay back to the steady-state level. A pulse test revealed that the positive power spike may have been caused by a loss-in-weight feeder mass flow upset. Figure 1.2 shows an example of a pulse test response (positive power increase and decay) that captured one of the periodic process transient dropout and recovery events.

A control engineer was then consulted to examine the data. The controls expert thought that the negative power dropout followed by the rise and decay looked like a Proportional + Derivative + Integral (PID) controller response to a large error between the setpoint and the measured mass flow rate in the polymer loss-in-weight feeder. The feeder manufacturer was then consulted and the extended team arrived at the root cause of the disturbance. When the loss-in-weight feeder hopper reached the minimum polymer weight, the controller switched from closed-loop mass flow mode to fixed volumetric flow during the refill cycle. When the refill cycle was completed, the controller switched back to closed-loop mass flow control mode. At the switchover, the PID controller detected a large error between the mass flow setpoint and the measured rate. The controller responded with a classical second-order response, a large, rapid drop in the auger screw speed output followed by an
Figure 1.2. Motor power dropout and recovery measured by a high-speed data acquisition system detected during a feed mass flow perturbation experiment.

increase and decay that depended on the tuning parameters. In this case, the PID controller used “aggressive” tuning for rapid response and did not possess a “bumpless” transfer capability when transitioning from volumetric to mass flow modes. The drop in throughput momentarily starved the extruder with a “negative polymer feed impulse” below the steady state flow rate. The dropout mass change was similar to the material added during the pulse perturbation test (several hundred grams). To compensate for the error, the feeder controller then responded by adding polymer pellets followed by the decay to the mass flow setpoint. The controller transition response caused a large torque change on the screws resulting in a loading change on the screw elements in the high-stress melting zone. The change in stress experienced by the screw flights could then be related to the mass flow rate change, which was effectively double that of the pulse test (dropout plus positive overfeed recovery). Ultimately, the screw element experiencing the periodic stress perturbation events failed.

This example shows that some difficult problems cannot be diagnosed by plant personnel using conventional monitoring systems using the “product by process” methodology. Additional expertise and sophisticated diagnostic tools were essential for troubleshooting in order to restore uptime to the manufacturing benchmark level. Mid-size to large companies can support diverse and leveraged engineering expertise to tackle such complicated problems. Small or highly cost-constrained companies can assemble the required expertise through external consultation and contract services. It must be noted that problems like this could require large expenditures over a long period of time (months to years) in order to find the root cause and implement a solution.

1.6.3 Polymer Degradation During Melt Processing

Condensation polymers, such as polyesters, can suffer from hydrolysis, thermal or thermal-oxidative degradation during melt processing operations. Improper polymer drying or process operating conditions can lower the molecular weight, resulting in inferior product properties in polyester films, fibers and molded parts. In this example, polyester degradation
was emulated on a batch mixer and laboratory twin screw extruder as a function of processing conditions and moisture level in order to characterize how melt compounding and film extrusion operations impact product quality [7, 8].

A steady-state monitoring method was applied to map the effects of polyester throughput \((Q)\) and extruder screw speed \((N)\) on mechanical energy input, melt temperature and Intrinsic Viscosity \((IV)\) [7]. While this method can be applied in a manufacturing environment, a production compounding process was scaled down to a laboratory-scale Coperion ZSK-30 mm co-rotating, intermeshing twin screw extruder. Polyethylene terephthalate \((PET)\) pellets were dried and then metered into the extruder. A data acquisition system was used to record the motor power and melt temperature. Analytical services were contracted to measure the Goodyear IV. The 30 mm extrusion data were used to develop a PET degradation kinetic expression as a function of \(Q\) and \(N\):

\[
\frac{d(IV)}{dt} = \frac{k_1 - k_2}{Q^2 N^2}
\]  

(1.2)

Where:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>(IV)</td>
<td>Intrinsic Viscosity</td>
</tr>
<tr>
<td>(t)</td>
<td>Time</td>
</tr>
<tr>
<td>(k_1) and (k_2)</td>
<td>Model parameter constants</td>
</tr>
<tr>
<td>(Q)</td>
<td>Throughput ((gm/s))</td>
</tr>
<tr>
<td>(N)</td>
<td>Screw speed ((revolutions/s))</td>
</tr>
</tbody>
</table>

Figure 1.3 shows the average motor power, melt temperature and IV as a function of rate \((Q)\), extruder screw speed \((N)\) and the estimated mean residence time \((t_{MEAN})\).

As expected, the mechanical energy input required to: melt, mix, and pump PET in the extruder was a strong, linear function of \(Q\) and \(N\). Melt temperature was mostly influenced by \(N\). However, change in IV was most sensitive to \(Q\). In subsequent analysis by extrusion experts (chemical engineers), IV loss was found to be most sensitive to residence time. This \(Q/N\) mapping method was used on laboratory equipment, under controlled conditions to quantify the effects of compounding conditions on the time-temperature-stress history during PET melt processing resulting in IV loss. The laboratory emulation revealed which process variables had the most influence on molecular weight. Once optimum conditions were established for handling and processing the resin, \(Q/N\) mapping could be used on the production equipment to quantify the effects of \(Q, N\), residence time and heat transfer on IV loss. However, experiments on the production equipment were required to establish a new correlation between \(Q, N\) and IV. This approach can be considered a "product by process" method.
Figure 1.3 Laboratory-scale twin screw extruder evaluation: PET degradation kinetics as a function of throughput and screw speed [7]. Upper left: Motor power vs. $Q$ and $N$, upper right: melt temperature vs. $Q$ and $N$, lower left: IV vs. $Q$ and $N$, lower right: IV vs. estimated mean residence time.

In order to understand the fundamental kinetics of PET degradation during melt processing, a batch mixer from DSM Research was employed [8]. The 15 cc capacity, co-rotating, intermeshing conical twin screw system with a recycle loop and sample valve was used to emulate extrusion conditions and generate samples for IV analysis. Figure 1.4 shows the normalized motor power measured for PET samples as a function of melt temperature and drying conditions.

While melt temperature had an effect on the degradation rate by thermal or thermal-oxidative mechanisms, the hydrolysis reaction was more significant. A second-order kinetic expression was derived as

$$\left( \frac{\partial P}{\partial t} \right)_x = -\frac{(a \cdot X + b)}{t^2}$$

(1.3)
Figure 1.4 Batch mixer evaluation of the kinetics of PET degradation as a function of melt temperature and moisture level [8]. Left: dried PET mixer motor power for two melt temperatures, Right: mixer power for dried and “wet” PET.

Where:

<table>
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<tr>
<th>$P$</th>
<th>=</th>
<th>Mixer motor power (J/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
<td>=</td>
<td>Time (s)</td>
</tr>
<tr>
<td>$a$ and $b$</td>
<td>=</td>
<td>degradation constants</td>
</tr>
<tr>
<td>$X$</td>
<td>=</td>
<td>hydrolysis coefficient</td>
</tr>
</tbody>
</table>

This kinetic expression was then applied to optimize a commercial PET compounding process in order to minimize IV loss and maximize first pass yield. Furthermore, it was demonstrated that drying equipment improvements were needed in order to reduce hydrolysis effects or eliminate the need for a downstream solid phase polymerization operation, reducing the capital cost and production cycle time.

This example shows how significant investments in leveraged chemical engineering and polymer chemistry expertise, analytical characterization services, and laboratory-scale processing facilities can be used to address very difficult problems in the manufacture of temperature and moisture-sensitive resins with minimum negative impact on uptime or yield (few and efficient manufacturing tests). Furthermore, new methods were developed and fundamental insights were gained that were then used to improve process design and operation. This knowledge can be leveraged and applied to other polyester resins when formulating and commercializing new products on existing plant equipment.
1.7 Conclusions

Expertise and resources to support troubleshooting activities may be drawn from many organizations within a company and through a network of external entities that includes consultants, contractors, suppliers and professional societies. The economics of troubleshooting represent a balance between maintaining and improving asset productivity (uptime, yield, customer satisfaction and other metrics) and investing in skilled labor, engineers, other experts, and supporting hardware and software. A company can realize a competitive edge by making sustained, strategic investments in resources with broad and deep expertise and experience in polymer processing technology and troubleshooting techniques.

References