Using lean methodologies for economically and environmentally sustainable foundries

***R. M. Torielli[1], R. A. Abrahams[1], R.W. Smillie[2] and R.C. Voigt[1]**

(1. Industrial and Manufacturing Engineering Department, The Pennsylvania State University, University Park, PA 16802, USA; 2. RWS Productivity & Consulting, L.L.C., Northville, MI 48168, USA)

Abstract: Lean manufacturing is often seen as a set of tools that reduce the total cost and improve the quality of manufactured products. The lean management philosophy is one which targets waste reduction in every facet of the manufacturing business; however, only recently have studies linked lean management philosophies with improving environmental sustainability. These studies suggest that lean manufacturing is more than a set of lean tools that can optimize manufacturing efficiencies; it is a process and mindset that needs to be integrated into daily manufacturing systems to achieve sustainability. The foundry industry, as well as manufacturing in general, has significant challenges in the current regulatory and political climate with developing an economically and environmentally sustainable business model. Lean manufacturing has proven itself as a model for both economic sustainability and environmental stewardship. Several recent studies have shown that both lean and green techniques and "zero-waste" policies also lead to reductions in overall cost. While these strategies have been examined for general manufacturing, they have not been investigated in detail for the foundry industry. This paper will review the current literature and describe how lean and green can provide a relevant framework for environmentally and economically sustainable foundries. Examples of lean and green technologies and techniques which can be applied to foundries in a global context will be described.

Key words: green manufacturing; lean manufacturing; environmental sustainability; pollution control
CLC number: TG221$^+$1 Document code: A Article ID: 1672-6421(2011)01-074-15

1 Introduction

The foundry industry faces specific challenges with respect to economic and environmental sustainability. Foundry processes require substantial energy, typically generated using fossil fuels; whether onsite or remotely at an electrical power plant. Melting the material consumes the majority of this energy; however, other energy intensive processes such as heat treatment are also included in many foundry operations. Also, a majority of foundries utilize sand as a molding material. The binders utilized can often include organic compounds, and, when burned out in the casting process, release volatile organic compounds and hazardous air pollutants which are regulated. The casting finishing process can also utilize organic materials which can result in environmental impacts[1]. Figure 1 shows a diagram of a typical foundry with potential waste streams.

***R. M. Torielli**

She has 24 years experience in manufacturing, primarily in automotive power train and foundry, including operations, quality, and human resource management. She is currently pursuing an Industrial Engineering Ph.D at the Pennsylvania State University, and teaching engineering courses and consulting with companies on lean implementation and environmental life cycle assessment. Prior to that Ms. Torielli spent 20 years at Ford Motor Company and held positions in Human Resources, Power Train Operations and Quality including: Manufacturing and Product Development Leadership Program, Power Train Manufacturing Quality Manager, Plant Manager of Windsor Aluminum Plant, Manufacturing Manager of Cleveland Engine Plant 2 and Quality Manager of Dearborn Engine and Fuel Tank Plant. She joined the Ford Motor Company in 1987 after completing her MBA at Case Western Reserve University. Ms. Torielli has been active in the past on the Board of Trustees of the Foundry Education Foundation and the American Foundry Society.

E-mail: rmt198@psu.edu

Received: 2010-07-08; Accepted: 2010-08-30

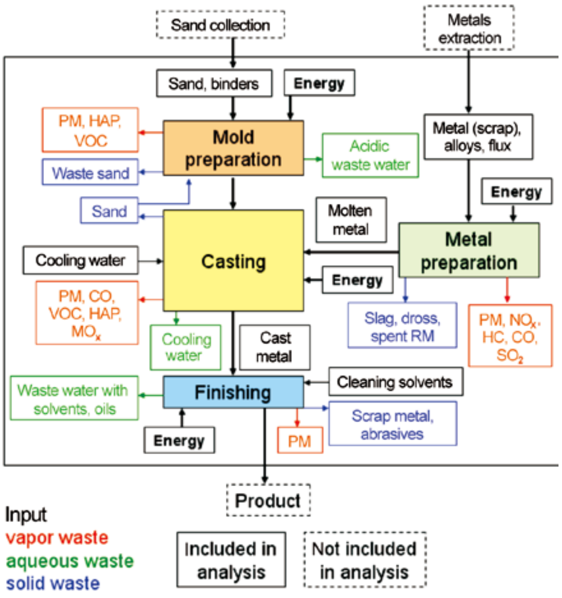


Fig. 1: Example of foundry system waste streams [2]

In addition to having environmentally sensitive processes, the business structure of the foundry industry has hindered its ability to develop and implement sustainable practices. The industry is primarily made up of small foundries with unique product and process combinations limiting the ability to develop technologies that benefit a large group of foundries. The small size of the businesses means that new energy saving technologies cannot be effectively capitalized. Also, because castings are typically viewed as a commodity by purchasers, profit margins are slim leaving little for the capital investment for major process changes. In addition, because many foundry processes such as melting furnaces and casting shakeout have exhaust systems subject to regulation, changes to these systems require lengthy environmental permitting procedures [1].

Despite the challenges, castings will continue to be critical components for many of the essential products for both developed and developing countries. Foundries can become economically and environmentally sustainable businesses with the systems approach offered by implementing lean and green methodologies.

2 Lean methodologies

The lean manufacturing movement was first highlighted in contemporary manufacturing by a five-year study done at Harvard University by Womack, Jones, and Roose which was published in a book called "The Machine that Changed the World" in 1990 [3]. In this book, the history of the automobile industry was studied and the quality and productivity improvement techniques applied by Toyota were termed "lean production". This production system, termed the Toyota Production System, TPS, is the over-arching framework and philosophy that can be used to organize manufacturing facilities and processes as well as to restructure suppliers and customers to provide best quality, lowest cost, and shortest lead time through the elimination of the several forms of waste and involving all the employees[4].

Despite Toyota's recent success applying a lean philosophy, Henry Ford is considered by some to be the father of lean thinking, and was reportedly a master at finding waste. In 1930 in his book "Moving Forward" Ford said, "It is the little things that are hard to see – the awkward little methods of doing things that have grown up and which no one notices. And since manufacturing is solely a matter of detail, these little things develop, when added together, into very big things" [5]. Waste reduction is typically seen as the heart of the "Lean Philosophy." Waste is broadly defined and can be thought of in a variety of ways. In his book on "Ford's Lean Vision", Levinson uses the word friction instead of waste. Friction can be defined as chronic problems and inefficiencies that become accepted aspects of a job and limit productivity [5]. The lean literature typically identifies seven or eight specific types of waste that must be attacked on the journey to lean. (Table 1)

Table 1: Eight types of wastes targeted by lean philosophy [6-7]

Waste type	Examples	Environmental impacts
Defects	Production of off-specification products, components or services that result in scrap, rework, replacement production, inspection, and/or defective materials	• Raw materials and energy consumed in making defective products • Defective components require recycling or disposal • More space required for rework and repair, increasing energy use for heating, cooling, and lighting
Waiting	Delays associated with stock-outs, lot processing delays, equipment downtime, capacity bottlenecks	• Potential material spoilage or component damage causing waste • Wasted energy from heating, cooling, and lighting during production downtime
Unnecessary processing	Process steps that are not required to produce the products	• More parts and raw materials consumed per unit of production • Unnecessary processing increases wastes, energy use, and emissions
Overproduction	Manufacturing items for which there are no orders	• More raw materials and energy consumed in making the unnecessary products • Extra products may spoil or become obsolete requiring disposal • Extra hazardous materials used result in extra emissions, waste disposal, worker exposure, etc.
Movement	Human motions that are unnecessary or straining, and work-in-process (WIP) transporting long distances	• More energy used for transport • Emissions from transport • More space required for WIP movement, increasing lighting, heating, and cooling demand and energy consumption • More packaging required to protect components during movement • Damage and spills during transport • Transportation of hazardous materials requires special shipping and packaging to prevent risk during accidents
Inventory	Excess raw material, WIP, or finished goods	• More packaging to store WIP • Waste from deterioration or damage to stored WIP • More materials needed to replace damaged WIP • More energy used to heat, cool, and light inventory space
Unused employee creativity	Failure to tap employees for process improvement suggestions	
Complexity	More parts, process steps, or time than necessary to meet customer needs	

As more and more companies attempted to become lean and struggled with lean implementation, it became apparent that applying lean as only set of tools on the production floor did not work. In his follow up book about lean manufacturing, Womack tackled the process to become lean and defined five-steps to guide its successful implementation [8]. These are:

(1) Specify value from the standpoint of the end customer by product family.

(2) Identify all the steps in the value stream for each product family, eliminating whenever possible those steps that do not create value.

(3) Make the value-creating steps occur in tight sequence so the product will flow smoothly toward the customer.

(4) As flow is introduced, let customers pull value from the next upstream activity.

(5) As value is specified, value streams are identified, wasted steps are removed, and flow and pull are introduced, begin the process again and continue it until a state of perfection is reached in which perfect value is created with no waste [8].

In 1988, the Shingo Prize, named for the industrial engineer Shigeo Shingo, was established. This prestigious prize was developed to honor the lifetime of work Shingo spent studying and developing lean cultures. The Shingo Prize Model (Fig. 2) however, is not just a production floor model. It is an overall systems model that incorporates all aspects of business operations and processes. The model was developed to promote lean/world-class business practices that result in ability to compete globally and demonstrates that culture is the foundation of a lean enterprise [9]. The Shingo Prize uses business metrics as a measure of success; thus, only companies whose positive results are driven by the transformation to lean are given recognition.

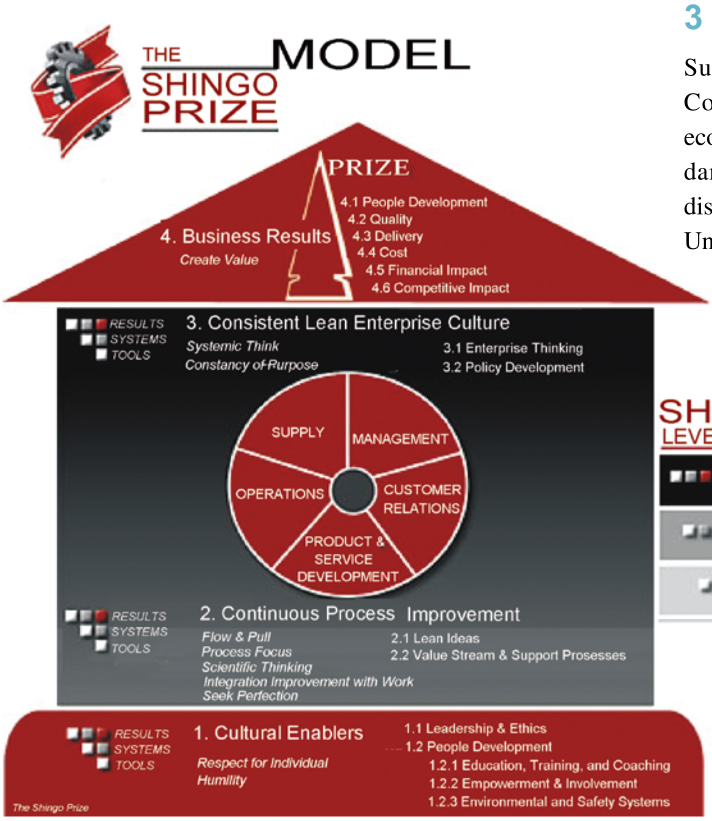


Fig. 2: Shingo Prize Model for lean enterprise

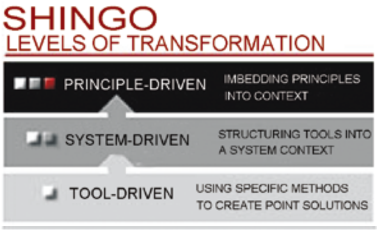
The Shingo Model recognizes “Cultural Enablers” as the foundation of a lean enterprise. Culture as a central lean implementation requirement is reiterated in the US Environmental Protection Agency (EPA) study of lean manufacturing and agreed upon by many other studies [6,10-13]. The EPA study exemplifies the characteristics of a successful lean organization with the following four statements:

- A continual improvement culture focused on identifying and eliminating waste throughout the production process;
- Employee involvement in continual improvement and problem-solving; Operations-based focus of activity and involvement;
- A metrics-driven operational setting that emphasizes rapid performance feedback and leading indicators; Supply chain investment to improve enterprise-wide performance; and
- A whole systems view and thinking for optimizing performance [6].

Lean is not a set of tools, it is a corporate philosophy and culture that abhors waste and works to optimize the enterprise as a system using several tools and techniques. From a sustainability perspective many, if not all, environmental impacts can be viewed as waste and must therefore be driven by poor systems thinking. It seems natural that the lean philosophy can be used as a powerful tool to improve environmental sustainability. The foundry industry in particular is an industry where efficient production and environmental impacts are closely tied, so the implementation of lean and green philosophies can have a powerful effect on a foundry’s economic and environmental sustainability.

3 Environmental sustainability

Sustainability was defined by the International Union for Conservation of Nature in a 1969 mandate as “achieving economic growth and industrialization without environmental damage” [14]. In part due to some highly visible ecological disasters, the concept gained more traction in 1983 when the United Nations published a report from the World Commission of Environment and Development, (now called the Brundtland Report), where sustainability was redefined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [15-17].



Environmental sustainability can be thought of in terms of natural capital, as the source for inputs and the sink for wastes such that you have both sustainable production and sustainable consumption within the biophysical limits of the overall ecosystem. However, the ability to balance production and consumption and also improve society with economic development is hard to measure resulting in little agreement on natural capital approaches to drive sustainability [18]. While definitions of sustainability are somewhat vague and a clear sustainability index is not agreed upon, most agree that there are three components to a comprehensive sustainability picture: economic, social and environmental [14]. This paper is focused on economic and environmental sustainability and will not discuss the social sustainability component.

Since the early 1990s environmental legislation and international environmental agreements have expanded greatly, driving global environmental policy changes [14]. It is in response to these policy changes, regulations, and the resultant increased public awareness that many companies have developed strategies and practices to become more environmentally sustainable. One such strategy is adopting Environmental Management Systems (EMS). In response to the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, the ISO 14000 Environment Management System standard was developed and published in 1996 [19-20]. The ISO 14000 standard is a widely used EMS, and will be used in this paper to illustrate EMS concepts and practices for environmental sustainability. The motivations used by companies for adopting EMS standards are mixed and they include industrial customer requirements, internal improvements, company image and better relationships with regulators [20-21].

The general nature of the ISO 14000 system illustrated in Fig. 3 demonstrates the basic concepts and definitions of environmental management [22]. ISO 14000 standards and guidelines can be grouped into three broad categories; management systems standards, evaluation and auditing tools, and product-oriented support tools [23]. Under ISO 14000, the specifics of a company's EMS are defined in the first category, management system standards. In 2001, the US EPA published a general implementation guide for EMS, which follows the ISO 14000 standard closely [24]. ISO 14000 mirrors the ISO 9000 quality management system standards. Both focus on systemic prevention rather than inspection (in the case of quality) and cleanup (in the case of the environment); and also prescribe a system for continuous improvement [15]. ISO 14000 does not require specification of clear environmental targets or guidelines; however, many companies who have implemented ISO 9000 quality improvement strategies and targets have also implemented similar ISO 14000 environmental strategies and targets [25]. An illustration of how various elements of an ISO 14000 EMS fit together is provided in Fig. 4 [26].

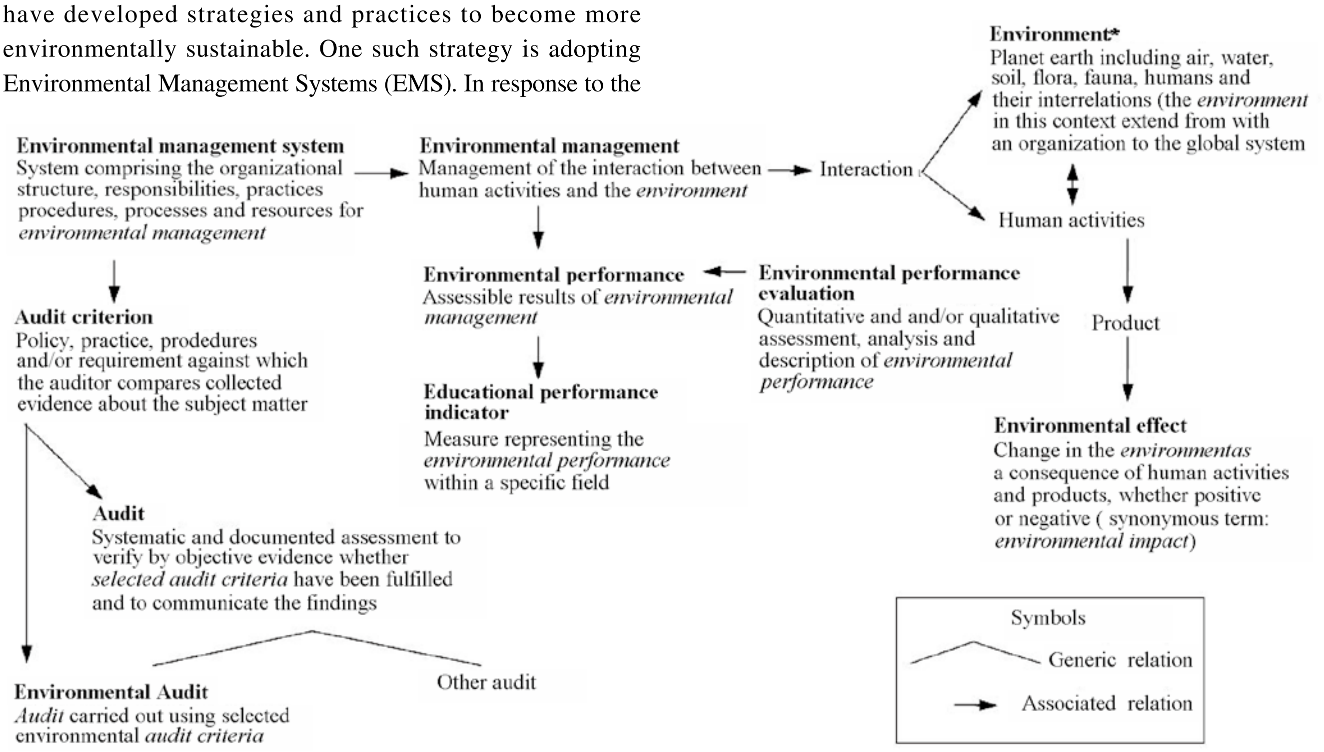


Fig. 3: Concept diagram and definitions related to environmental management [22]

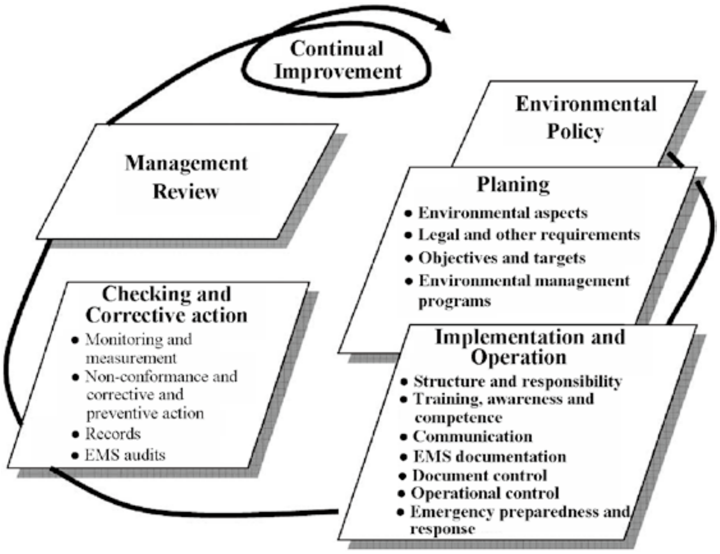


Fig. 4: ISO 14000 elements and how they interact [26]

Some type of Environmental Management System is an essential tool that must be used to ensure environmental sustainability for companies around the globe. The debate on the appropriate measures and subsequent regulations for environmental sustainability continues, and in response, more companies continue to be impacted by the increasing number of environmental regulations and policies. The foundry industry is increasingly impacted by new regulations and guidelines, and thus tools and techniques for managing environmental sustainability are very important.

4 Studies linking lean methodologies with environmental sustainability

Prior to 2000, strong links between the implementation of lean philosophies and improved environmental sustainability could be found in words only. An early reference found in the Harvard Business Review (HBR) article casts doubts on whether win-win situations can be found for business when trying to improve environmental sustainability. However, the article concludes that environmental impact management needs to be managed as trade-offs using a value based approach, philosophically very similar to the lean approach [27]. Also in 1994, The United States President's Commission on Environmental Quality issued a report on "Total Quality Management: A Framework for Pollution Prevention" where TQM and pollution prevention were seen as complementary processes [28]. While this report received limited exposure, the direct application of lean philosophies, such as TQM, to environmental sustainability had not been previously reviewed. The report also lists success stories where TQM had tremendous impact on pollution prevention [28]. Later, results of a 1996 study found that adopting manufacturing process innovation (this study's term for lean) incentivized the adoption of environmentally friendly manufacturing practices. The adoption of lean techniques drove the adoption of green design and manufacturing because they are structured by similar principals: a dedication to productivity, quality, and cost reduction, continuous improvement, and technological innovation [29]. A second Harvard Business Review article states that enhanced resource productivity, those things that also drive reduced environment impact, can be expected to enhance corporate competitiveness. Secondly, this article suggests that properly designed regulations would trigger innovation that would improve cost, improve value, and at the same time improve environmental impacts [30]. A 2000 study on the furniture industry using interviews and surveys found that despite seeing the environment and lean practices, such as Just In Time (JIT) or Total Quality Management, as separate initiatives, process changes for the improvement of environmental performance delivered competitive economic performance improvements [31].

Corporate activity linking lean techniques and environmental sustainability have been accelerated since 2000; there is a growing body of literature linking the two. Environmental sustainability management activities have been studied focusing on different areas of lean: manufacturing; supply chains; management, organization structure and community partnerships; and enterprise. Recognizing that lean manufacturing methodologies were a leading manufacturing paradigm, and that lean efforts in the area of waste reduction had great potential to create positive environmental outcomes. The US Environmental Protection Agency (US EPA) commissioned 5 test cases at the Boeing Company to focus on lean waste reduction [32]. This US EPA study came to the following conclusions:

- Lean produces significant resource productivity improvements which lead to environmental improvements.
- Lean produces a robust waste elimination culture.
- Lean thinking brings powerful financial incentives to resource conservation and pollution prevention improvement [32].

Subsequently, in 2003 the US EPA issued another report on lean manufacturing and the environment, and dedicated a portion of their website (www.epa.gov/lean) to the link between lean manufacturing and environmental sustainability [6]. The US EPA has also published toolkits for applying a few chosen lean tools to improve environmental impacts and energy efficiency [7, 33]. The lean and environment toolkits identify the environmental impacts that could result from six of the eight types of waste targeted by a Lean Philosophy. These environmental impacts are listed in Table 1 alongside the 8 wastes targeted by lean manufacturing.

An empirical analysis of over 17,000 firms using large scale databases from several sources using a regression model found that adopters of ISO 9000 were more likely to also adopt ISO 14000. Also, adopters of ISO 14000 had lower total emissions, and, lean producers and lower inventories were complementary to waste reduction and pollution reduction [34]. The book "Henry Ford's Lean Vision: Enduring Principles from the First Ford Motor Plant" asserts that with aggressive use of Lean techniques, adding an ISO 14000 EMS is not only free, but profitable. He further states that lean, ISO 9000 and ISO 14000 are not separate activities, but mutually supportive. The ideal implementation of lean is to have nothing to salvage, meaning that materials have been used productively or not at all, which in turn leads to better resource productivity. Numerous examples are given where waste products become by-products which are either used or sold [5]. More recently, lean operating systems and environmental management systems were compared and parallels similar to those identified by the earlier US EPA Boeing study were found. Those parallels were expanded and lead to the development of the comprehensive lean and green system model shown in Fig. 5. These comparisons concluded that the strength of the management system correlates with the positive business results for both lean and green [35].

A statistical analysis of green management system measures against the Shingo Prize scoring elements Shingo Prize winners from 2000 to 2005 showed that green manufacturing initiatives improved lean implementation scores. This finding reinforced findings that lean by itself does not drive environmental improvements, but is synergistic when

Fig. 5: Comprehensive lean and green system model [35]

environmental initiatives are included. The use of less toxic, more recyclable, or more easily processed materials was significantly correlated to increased profits as well as increased customer satisfaction and profitability [36].

Research on lean supply chains show mixed results when looking at resulting improvements in environmental sustainability. Green Value Stream Mapping is a holistic approach to remove waste from the entire supply chain resulting in increased customer value and efficient resource utilization, thus decreasing environmental impact [37]. However, enforcing green concepts into the supply base can be tricky [38]. Suppliers may balk if environmental activities reduce their profits, as a reduction in overall material usage is wont to do; thus strong supplier relationships are a key element in effective lean and green initiatives. A simulation model of a generic supply chain including various lean techniques tested the assumption that lean systems compress time-to-market, and in turn reduce a key environmental performance factor – carbon dioxide (CO_2) emission. The resulting analysis showed that the CO_2 emissions were very sensitive to raw material delivery frequency and mode, and that implementing lean techniques, especially in the supply chain portion of the enterprise, did not drive environmental improvements if the environmental impacts were not a direct measure along with other business measures [39]. Supply chain and supplier relationships were again noted as an important part of any lean enterprise. The link between two specific lean practices, continuous improvement and supply chain practices, and environmental management programs were evaluated. Effective environmental management was found to have a significant positive impact on delivery, confirming the synergistic relationship between environmental activities and lean implementation. The alignment between environmental activities and lean activities has been found to be critical factor in company competitiveness [40].

In addition to the relationships with the supply base, many papers have highlighted the impact organizational structure and community partnerships (such as those with regulators) are important to the success of environmental sustainability within a lean framework. The implementation of lean and the role of employees at all levels in environmental improvements are discussed using data from the Toyota / GM joint venture, New United Motor Manufacturing (NUMMI). The role of specialist staff, especially the environmental engineer, is critically important in making environmental improvements; however, more than one type of knowledge is required. Thus culture and management structure, especially those fostered by lean enterprise thinking, encourage the combination of knowledge sets to make environmental improvements [11]. It has also been reported that environmentally sensitive processes were more difficult to make lean and will require technical innovation and closer ties with regulatory agencies [6] [32].

It should be noted that investment in environmental abatement technologies is counter to lean philosophies in that abatement does not directly improve the value of the product to the customer and can be considered non-value added in all cases [41].

Lastly, lean thinking dictates that the economic and environmental sustainability of a company should consider the both a holistic enterprise view of the company and the product life cycle. The integration of environmental and economic sustainability can be viewed from an operational and a strategic perspective. In the late 1990's Ford Motor Company adopted environmental sustainability as a corporate strategy. This strategy was instrumental in Ford launching the first American built hybrid, the Escape, and in the construction of the Ford Rouge Center which includes a green roof and ten acre sedum garden. Figure 6 shows one framework for manufacturing sustainability which includes three dimensions of sustainability, three strategies for sustainability, and four layers of corporate organization. This viewpoint is reflected in the research findings that traditional economic variables are now being combined with ecological metrics. The authors also performed a simulation of Lean methods such as Zero Defects and Kanban in different combinations, and compared the impacts on the ecological metrics such as energy usage. Production efficiency is positively correlated with production efficiency. They also concluded that lean production techniques alone won't yield ecological benefits. A holistic enterprise view of lean and sustainability is required to make the correct trade-offs [4].

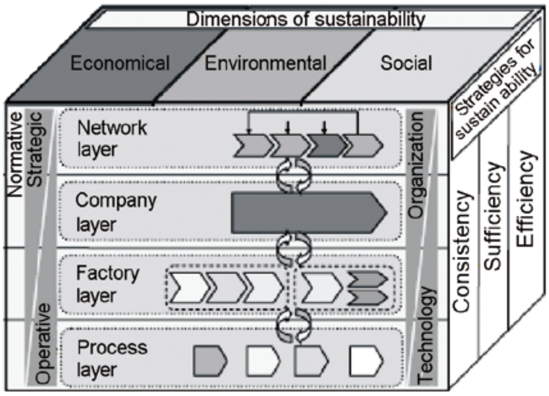


Fig. 6: Framework for sustainable manufacturing [4]

Another view of sustainable manufacturing is the three legs of the triple bottom line concept – people, planet, and profit (i.e., social equity, environmental quality, and economic prosperity) as synergistic measures of the success of a given enterprise. This viewpoint drives a recommendation for using an integrated material, energy, and waste flow model which includes the generic life cycle of the manufacturing system. The scope of the model would include product design, process selection, and facility design because all three have an impact on life cycle. Figure 7 shows an example of high level energy flow model for a simple shot peened product. While the shot peen process utilizes a significant amount of energy, the impact on the final product's design and useful life can offset this [25].

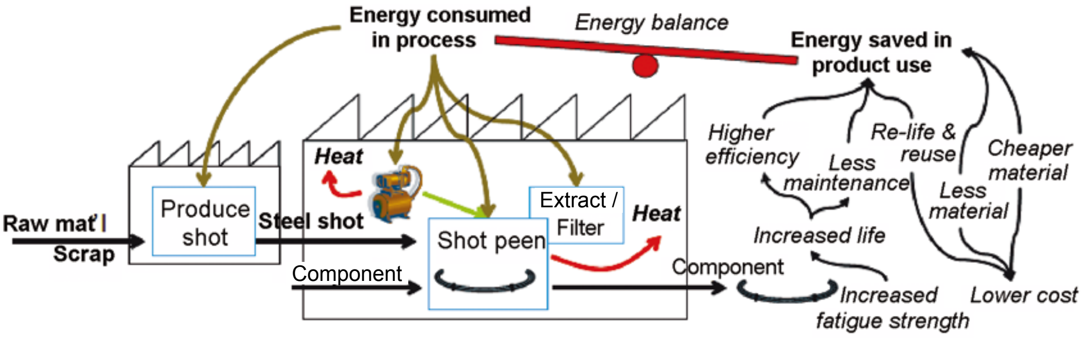


Fig. 7: Energy flow map in a shot peened product [25]

Although the integrated enterprise view and the product life cycle view can help generate sustainability ideas for potential synergies outside of the normal scope of a given manufacturing site; they add a complexity to the implementation of ideas to improve lean and green efforts which are beyond the capacity of many small and medium-sized organizations.

Foundries are challenged by highly regulated, energy intensive processes; however, the successful integration of lean and green in the foundry industry has been demonstrated. In the late 1990s Ford's Windsor Aluminum plant became the first North American metal casting plant to be awarded ISO 14001 registration, and included the EMS as part of their overall lean operating philosophy. Literature and experience demonstrate that the synergy between the efforts offer great benefits to the foundry industry.

5 Framework for foundry lean and green implementation

In Fig. 8 a framework for implementing lean and green methodologies is illustrated. The bedrock for implementation is the organizational philosophy. The supporting pillars for implementation are process improvement: throughput improvement, energy efficiency, innovative technology, and community partnerships.

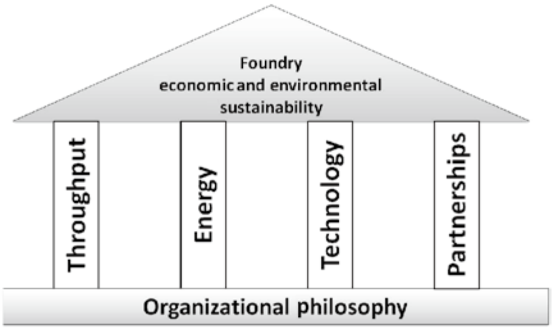


Fig. 8: Framework for foundry lean and green implementation

Organizational Philosophy – Lean manufacturing, including environmental sustainability, is an organizational philosophy or mindset, not a set of tools which can be used selectively. Lean thinking is synonymous with systems thinking; optimizing the whole against multiple objectives. To maximize waste reduction of all forms the philosophy must be genetic in the organization. It cannot be viewed by the employees as an option or "just another initiative." The employees will not embrace sustainable lean and the organization will not achieve the expected results without direct involvement. The involvement of every employee at every level of the organization is crucial. No level can be left out, especially middle management or floor supervisors. In the end it's the "people that make the difference" and make the organization function. A key tool for ensuring philosophical alignment and understanding is the Management Operating System, and 5S and Safety.

Throughput Improvement – A cornerstone of the lean and green implementation is efficient use of resources, or the elimination of waste. In the foundry this efficiency can be achieved through increased throughput of materials.

Throughput can be split into eliminating scrap and non-value added activities, increasing productivity through constraint analysis, as well as increasing production efficiency such as casting yield. Improvements in production efficiency can have both a lean and green cascading effect throughout the foundry. Tools and techniques which support throughput include 5S and Safety, Green Value Stream Mapping, Statistical Process Improvement, and the Management Operating System.

Efforts should be made to eliminate not only scrap but also non-value added activities within the casting and finishing processes which can all be considered forms of waste. Casting scrap is pure waste, so efforts to reduce scrap impact the economic and environmental sustainability of a foundry. Scrap casting repair and welding are non value added operations and the cost cannot be passed on to the customer. These type of operations are actually waste and should be eliminated from the process. Once the plant floor understands that welding and repairs are no longer accepted by the customer, the foundry can make strides to correct the problems which lead to these issues.

Productivity improvements will also lead to improvements in operating cost, and in energy reductions, as the operating time to produce customer demands is shortened. Lean methodologies can assist in making these productivity improvements. For example, a Canadian aluminum casting plant was able to improve their cylinder block jobs per hour level from 30 to 35 jobs per hour by understanding and eliminating blocked and starved constraints within the manufacturing process. Little additional investment was required to accomplish the task. Costly overtime hours were eliminated because the improved system throughput and on time delivery to the customer were achieved.

Foundries can also focus on casting yield as a specific area for throughput improvement. Yield improvements reduce the amount of material required to produce the product, and the overall energy and material usage for a given customer demand. Yield improvements can occur through improving nearer net shape of casting and increasing the efficiency of the metal feed. If the process can be controlled there will be much less variation and movement in the mold leading to greater near net casting shape. Significant facilities and tooling investment can be reduced in the casting finishing department if the casting processes can be designed and controlled so that they are more repeatable. The metal gating and risering system itself can be viewed as waste, as the gating and risering system must be removed and is typically recycled through remelt – an energy intensive process. Optimizing the size and location of risers and the use of efficient gating systems minimize this waste [42]. Significant casting quality improvements have been documented since the utilization of computer simulation solidification models. Computer modeling packages are useful for both gating/risering and mold filling evaluation. Using rice hulls as an exothermic material for an open riser is an example of two lean techniques for the foundry, improving yield, and beneficially using a waste product.

Material reductions within the foundry have impact back to the mining process, reducing the overall life cycle environmental impact. Figure 9 illustrates the lifecycle of an aluminum billet used as aluminum foundry melt stock. It shows that emissions and wastes are generated far upstream in the source to final product system. Each unit of material saved in the foundry will save these emissions and wastes.

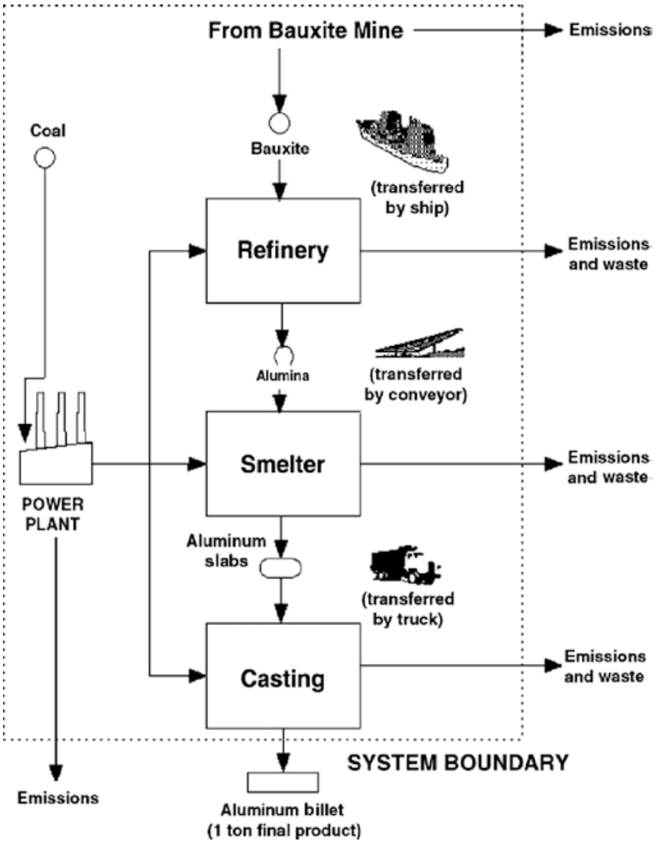


Fig. 9: Aluminum source to final product system diagram

Energy Efficiency – As stated in the introduction, foundries are energy intensive operations. While on-site generation of greenhouse gases through the heat generated via the burning of coke or natural gas is a major concern for foundries, data from the U.S. Energy Information Administration Environment website identifies the generation of electricity as the number one source for foundry greenhouse gas emissions. Energy use is typically not a metric that is employed in manufacturing systems design [25]. Yet, as shown in Fig. 9, the efficient conversion of a fuel to desired output is diminished in the many phases of electrical generation, transmission, and use. Thus, efforts at controlling and reducing electrical energy usage in the foundry have magnified environmental benefits and should be targeted in lean and green efforts.

Techniques to improve energy consumption used in conjunction with the other waste reduction techniques contained in the lean toolset, not only provide energy reduction, but also improve costs [43]. Tracking energy flows through the system using a Green Value Stream Map is one technique that can be used to reduce consumption. An example is compressed air, often used in foundries. In the UK 10% of the total energy supplied to industry is used to compress air. As little as ten percent of the energy supplied to air compressors can be converted to useful energy [25]. When tracking energy use through the system, minimizing the use of compressed air can improve both cost and environmental impacts. Tracking energy use is vitally important to lean strategies that drive environmental sustainability. Other techniques which can help improve energy usage are Management Operating System, Green Value Stream Mapping, Statistical Process Improvement, and 5S and Safety.

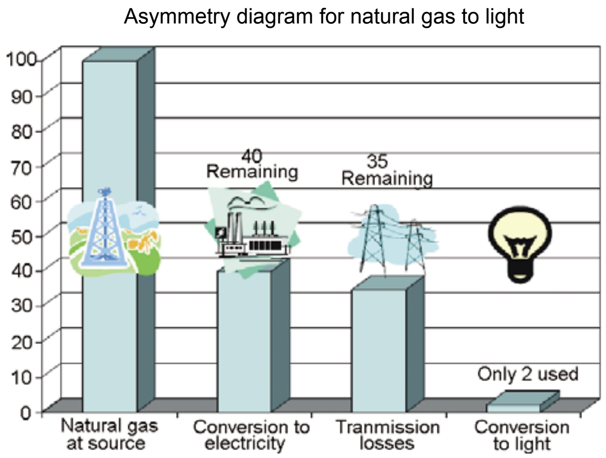


Fig. 10: Losses in net energy from source to sink [44]

Innovative Technologies – While lean manufacturing techniques can make improvements in a foundry's economic and environmental sustainability, innovative technologies may be required to make large breakthroughs. Emissions requirements have grown considerably more restrictive for foundries with the enactment of the 1990 Clean Air Act [45]. While there are many possible theoretical solutions for reducing foundry emissions, acceptable solutions must also be financially sustainable. To preserve the viability of foundries, both researchers and industry have developed a number of approaches to decrease emissions from foundries. Strategies range from reformulating chemistries of organic binders to developing processes for conditioning sand to lower the amount of released organic compounds and reduced binder levels by better core blowing. Two specific innovative technologies, Advanced Oxidation and OP-AID, have proven to both improve cost and reduce environmental impacts. Identifying opportunities for innovative technologies can be fostered through the Management Operating System, Green Value Stream Mapping, and 7R.

Community Partnerships – While perhaps the most difficult process improvement, one which has the greatest potential for environmental sustainability is developing community partnerships. Community partnerships can include community outreach activities, partnerships with regulatory agencies, and partnerships with suppliers and adjacent industries. Community outreach can be as simple as activities designed to educate the community surrounding your facility about your efforts to reduce waste. Better still is to take a leadership role in the community environmental efforts such as recycling program leadership. These efforts will improve relations and reduce complaints based on misinformation, and provide a solid footing for your lean efforts.

Many environmental regulation agencies are recognizing that a command and control type of emissions regulation systems are limited in their ability to improve environmental impacts. Some agencies are embracing innovative strategies for environmental stewardship. Most process changes within the foundry will have environmental impacts. Therefore, technical innovation will often require a close partnership with regulatory agencies even if changes reduce emissions or solid wastes at the foundry. A good example of this was Benzene Reduction Action Team formed in Wisconsin between the Wisconsin Department of Natural Resources and a trade organization for Wisconsin metal casting companies which helped these companies meet hazardous air pollutant regulations [46].

Additionally, other manufacturing industries can also become partners if the foundry's system viewpoint is broadened. Many apparent waste products from one industry can be beneficially reused by another. For example, the Portland Cement Association (PCA) of the US and Canada, were able to reduce their emissions considerably in recent years by using alternative materials. They were able to put to use waste materials from the steel and foundry industries, including slag and waste foundry sand [47]. There are many examples of this type of industry synergy. Lean tools which facilitate the discovery of these synergies are Management Operating Systems, Green Value Stream Mapping, and 7R .

The framework described here and its key elements for foundry implementation of lean and green methodologies are just a starting point. Several references are cited in this paper which can provide more in-depth information.

6 Tools, techniques, and technical innovations for lean and green foundries

As previously stated, lean is a philosophy and not simply a set of tools and techniques. However, some key lean tools and techniques have proven especially effective in improving foundry sustainability. Figure 11 shows a mapping of these key tools to the elements of a foundry implementation framework. It shows how lean implementation is an integrated system, with several key elements of implementation utilizing many of the same tools or techniques. These include Green Value Stream Mapping, 5S and Safety, Statistical Process Improvement, and 7R. What follows is a brief description of each tool or technique.

Green Value Stream Mapping – A value stream map (VSM) is a simple diagram of the material flow through the system that shows where waste is occurring. One of the best resources for how to create a value stream map is the book "Learning to See" [48]. A value stream map can be constructed for the entire enterprise or for a single production

key lean tools enabling foundry lean and green implementation framework	Organization philosophy	Improve throughput	Energy efficiency	Innovative technologies	Community partnership
Green value stream mapping		×	×	×	×
5S and safety	×	×	×		
Statistical process improvement		×	×		
7R				×	×
Management operating system	×	×	×	×	×

Fig. 11: Mapping key lean tools to a foundry lean and green implementation framework

line. While a powerful tool for lean, a VSM typically focuses on the forward product material flow and does not typically consider other material flows and waste streams, especially energy [25]. A Green Value Stream Map (GVSM) includes not only the material flow through the system, but also all of the energy and waste flows. The GVSM process can be used to identify sources of emissions, opportunities for improvement in material and energy usage, non-value added activities, and to provide a roadmap for possible innovative technologies and community partnerships. It can also be good communication tools among the stakeholders for all these activities. The technique has been applied effectively to improve both cost and environmental impact. For example, a bicycle manufacturer in China analyzed the flows of water, energy, and solvent pinch in the painting and drying processes independently which then resulted in one process preheating the air intake for the others [25].

In addition to looking at just the present flow of material, energy and waste in the system, GVSM can be used to also look at the lifecycle of the product. ISO 14000 provides guidelines for Life-Cycle Assessment (LCA). LCA traces the major steps and processes over the life of a product covering: raw materials extraction, manufacturing, product use, recycling and final disposal. It identifies and quantifies the environmental impacts at each stage [49]. LCA techniques are used extensively in the industrial ecology field which seeks to optimize the life cycle of virgin materials through to ultimate disposal in the pursuit of sustainable manufacturing [25]. Since the prior processing used for many raw materials used by the foundry industry is energy intensive and environmentally sensitive, taking a GVSM life cycle view can demonstrate how improvements in foundry processes have impacts outside of just a specific site. GVSM can also improve communication with community partners, such as regulatory agencies, to gain support for regulatory practices that offer true life cycle improvements rather than just plant-level environmental improvements.

5S and Safety – 5S is an acronym for activities which provide for an ordered workplace in which visual cues can facilitate problem detection and resolution. In English, the 5S's stand for Sort, Straighten, Shine, Standardize, and Sustain. Frequently Safety is included as a sixth 'S' because of its importance to the workers and to the community. Lean manufacturing principles ultimately target the elimination of all forms of waste. The 5S process follows the same philosophy and helps to identify what is waste so that it can be eliminated. A 5S cornerstone is "the right thing in the right place at the right time"; anything else should be disposed of in a safe and environmentally correct manner. When a workplace is implementing 5S, it is very evident to both workers and visitors; providing physical demonstration of the organization's lean philosophy. Maintaining 5S reinforces that management commitment to lean philosophy. 5S is a key element of an overall Management Operating System in that items which need management attention and oversight are blatantly visible to all, fostering the common understanding of what is important. From an environmental sustainability perspective, 5S calls attention to uncontrolled waste and/or emissions because they do not fit the standard. 5S can assist with energy efficiency by calling attention to machines and items which should or should not be running given standard operating procedures. Also, indicators can be developed which visibly show when a system is not operating correctly. A clean floor will quickly show a leak in a system, where material is being wasted. Finally, the 5S process can dramatically change the appearance of a foundry, and can improve the foundry's reputation among employees (current and prospective) and the community.

Statistical Process Improvement – A key tool supporting lean implementation are probabilistic and statistical methods required to improve the quality of products and processes. Six Sigma methodologies incorporate a toolbox of statistical process improvement (SPI) techniques that can effectively drive sustainable process improvement. It is crucial to identify the true root causes of waste and SPI insures that those root causes and the corrective actions will truly impact those wastes significantly. Statistical Process Control (SPC) Charts can be an important part of both a Management Operating System and the 5S process in the foundry to drive improvements in both process control and environmental control. SPI can be used for reducing foundry scrap with resulting cost and sustainability benefits. Designed experiments can be used to make process improvements as well as environmental improvements. SPI techniques can be powerfully used to develop better understanding of material and energy usage, production line productivity, and environmental impacts. SPC charts can be used for controlling electrical usage, or improving emissions.

7R – Another key thought process or technique is 7R. Originally just 3 R's, which stand for Reduce, Recycle, and Reuse; this mnemonic is a quick reference when looking at materials coming into the system, and wastes leaving the system. These were expanded to 7R's [50], and now include Remove, Renewable, Revenue, and Read. The thought process is simple: can any material in the system create less environmental impact by using any of the 7R's? Can it be removed altogether? Can the usage be reduced? Can the product be reused, or recycled in house or by a partner industry? Can the waste be sold (i.e. revenue)? The last R, read, is to encourage employees and organizations to research the possible uses for their waste materials through reading. A key lean method which supports the 7R technique is 5S because avoiding the mixture of waste streams through clear labeling is helpful. For example, an aluminum foundry machine shop pioneered dry machining techniques which facilitated the re-melting of the aluminum machining chips because they were not contaminated with cutting fluids. Additionally, this same foundry recycled zircon fines, a waste product of their thermal sand reclamation system, to investment casting companies as a raw material. Another example is the beneficial reuse of cupola slag as a material for concrete manufacturers. The value of these materials was improved by the ability to keep them clean and separate from other waste material streams. 7R supports a foundry's ability to form community partnerships and helps drive innovation in processes such that the by-products of that process have value.

Management Operating System – While lean is a holistic system for managing any business, the method to manage that system must itself be lean. Thus a lean Management Operating System is crucial to the foundry lean and green implementation framework. Like 5S, and as part of 5S, the Management Operating System hones the requirements to insure operational success just to the crucial items, and discards the rest [51]. The management system is transparent and visible to all of those working and visiting the facility. The process supports the foundry's lean philosophy by insuring that managers and supervisors can 'walk the talk' with a consistent message and consistent performance measures including sustainability measures. A lean management team will determine the key goals for the organization and the measures of success, usually with a process which insure the input of as many people in the organization as possible. This insures buy-in. It is important that the number of metrics is limited, that they are reviewed regularly, and that key metrics, including environmental metrics, are visible to everyone in the organization. It is also important that these measures are consistent and aligned throughout the organization. Ideally, the process reinforces the lean organization philosophy regularly. It measures improvements in throughput at each level of the organization. It includes environmental impacts, such as energy usage and emissions. It asks on a regular basis whether innovative technologies exist to make improvements, and drives partnerships.

7 Technical innovations

To demonstrate the potential for technical innovation to advance the economic and environmental sustainability of foundries, two technologies which have been implemented successfully are described in detail in this section. We describe two different innovations: Advanced Oxidation (AO), which is performed in conjunction with sand conditioning, and OP-AID, which is used to reduced waste in terms of energy during the heat treatment of castings.

7.1 Advanced oxidation

A large majority of the foundries in the United States are green sand foundries. Green sand in use generally consists of silica sand, bentonite clay, and carbon additives (usually seacoal), and water. In many cases, the complexity of shapes requires the use of cores. Core sand itself is generally made with sand and some form of curable organic binder as opposed to clay. Core sand requires stronger binding than that of the clay-bound bulk sand to produce acceptable castings, as they generally support more weight per unit area than that of the surrounding green sand. In either case, organic compounds are present in the forms of the resin used and/or the organic compounds contained within the mixtures. Because of the inclusion of these carbonaceous materials, many reactions occur at high temperatures which can have both positive and negative effects on casting quality and emissions. When pouring ferrous castings at high temperatures, seacoal transforms into a soft formable coke barrier which prevents excessive metal penetration into the mold. The coal also reacts with metal-mold boundary oxygen to form carbon monoxide and other oxygen-rich species, preventing the formation of surface iron oxides. In addition, these gases provide a surface blanket which allows for improved surface finish. However, further from the casting surface, organic compounds in the mold are subjected to cooler temperatures which leave the pyrolysis reactions essentially incomplete [52]. These intermediate temperature reactions lead to release of relatively large amounts of VOC's from both core binder and seacoal decomposition. In terms of core sand, a characterization study revealed that phenols, cresols, benzene and toluene tend to be the main components of pollutant releases in terms of resin binders. In addition, these high temperatures lead to the loss of hydroxyl groups on the surface of the clay, preventing hydrogen bonding, and therefore creating "dead" clay. This dead clay becomes a solid green sand system component that must be removed from the sand system. Additional clay and seacoal must be added to restore the binding properties of the green sand after each molding cycle.

The integration of advanced oxidation (AO) processing into green sand systems represents not only a way to improve emissions, but also to reduce material input and solid waste costs. In the United States, advanced oxidation systems have been installed on 15–20 active green sand production lines, with measured VOC emission reductions from 20%–75% [53]. It is also important to note the use of AO leads to the complimentary reduction of raw material inputs to the green sand system that further reduce sand system VOC emissions. While green sand foundries recycle a great deal of their molding sand, new sand, seacoal and clay must be continually added to make up for breakdown due to continuous cycling through severe conditions. A large green sand foundry (200,000–300,000 tons/year of casting weight) has been estimated to require 50,000 tons of silica sand, 20,000 tons of clay and 6,000 tons of seacoal yearly. AO processing alone allows for a system to retain a significant portion of the useful clay that would normally be exhausted into baghouses and discarded. With the addition of ultrasonic cavitation processing, both baghouse active clay and waste green sand active clay can be reclaimed and material additions can be curtailed [54].

There are three basic designs of AO systems in use. First generation advanced oxidation-clear water systems (AO-CW) work by treating incoming water with hydrogen peroxide and ozone additions under sonication. This water is then added to sand through mullers and cooling systems for cooling heated sand. Advanced generation systems, which include advanced oxidation dry dust to blackwater (AO-DBW) and advanced oxidation blackwater from wet collector systems (AO-BW-WC) work with particulate collection systems to return a portion of "useful" clay which remains trapped in baghouse fines and waste green sand. In traditional non-AO systems, active clay contained within these fines remains trapped due to a hydrophobic organic coating acquired during the high-temperature processes of casting. During AO processing these dry fines collected from baghouse dust and/or wet collection sludge are combined with water to form what is called "blackwater." This blackwater is then AO-treated, and hydroxyl and other electronegative ions react with the organic coatings. The water is then sent to a settling tank where inactive fines settle, leaving AO-treated blackwater with active clay to return to the system, preserving active clay. With an optimized AO system, pre-bond additions have been reduced by 25%, while green strength has increased a small but significant amount at the same time [55].

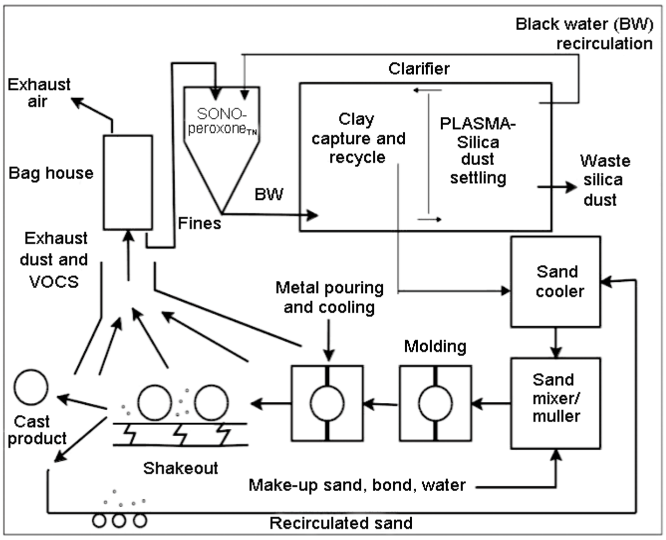


Fig. 12: Simplified model of AO assisted green sand system [52]

Table 2: AO system performance summary at production iron foundries [55]

	AO	AO-BW	AO-UCS
Emissions	• Benzene emissions reduced 10%–30% • VOC emissions reduced 20%–40%	• Benzene emissions reduced 20%–50% • VOC emissions reduced 30%–75%	• Benzene emissions reduced 20%–50% • VOC emissions reduced 30%–75%
Sand system performance	• Clay consumption reduced 15%–35%	• Clay consumption reduced 15%–35% • Blackwater, clarifier active clay recovery improved by an estimated 10%–20%	• Clay consumption reduced 15%–35% • Recovery of 60%–80% of the active clay from sand system baghouse dust
Other benefits	*• Reduced in-plant smoke and odor from pouring, cooling and shakeout* *• Reduced stack odor* *• Reduced ductwork build-up of condensable organic compounds*		

Further development of AO systems in foundries continues. Ultrasonic cavitation systems (UCS) have been developed to augment early AO system designs. In addition, there is further generation of hydroxyl radicals, as the energy from ultrasonic waves has been found to break bonds in peroxide containing water that assist in VOC destruction [56]. UCS systems take up about one fifth of the floor space as compared to an early AO-BW clarifiers and cost about a quarter of the price. With the addition of ultrasonic cavitation, the amount of baghouse dust that can be retained in the slurry can be tripled, leading to increased retained clay and significant reductions in clay additions over early AO- system designs. Furthermore, VOC emissions were further reduced by two-thirds when employing UCS with AO as compared to AO-CW systems [57].

Research continues in developing AO-UCS systems for not only emissions reduction and baghouse dust clay recycling, but also for the purpose of green sand reclamation for use in the core room. For core sand recycling, organic residues left from resins and other bonding media are often stubborn and difficult to remove. Similarly, complete removal of green sand clay and carbonaceous coating for rebonding in the core room is very challenging. The traditional methods of reclamation are often energy and capital intensive. For example, thermal reclamation systems heat sand between 500–800℃. Not only are large amounts of heating energy required, but valuable clay is destroyed as both calcium and sodium bentonite degrade at temperatures between 450–620℃. Traditional wet reclamation methods require large amounts of water, large amounts of floor space, and inadequately remove clay and other organics from sand [57-58].

Using AO-UCS systems, MB clay on reclaimed green sand was reduced from 7.92% to 0.4%–0.6%. LOI was reduced similarity from 3.8% to 0.4%–0.6%. With a 60% AO-UCS reclaimed mix to 40% new sand mixture used in coremaking with conventional PUCB binders and binder levels, core tensile strengths of about 120 psi were reached. In addition, the size distribution of sand for processing can be adjusted through AO-UCS process parameters, so that reclaimed sand can be used for core sand and/or returned to the green sand system in place of new make-up sand [58].

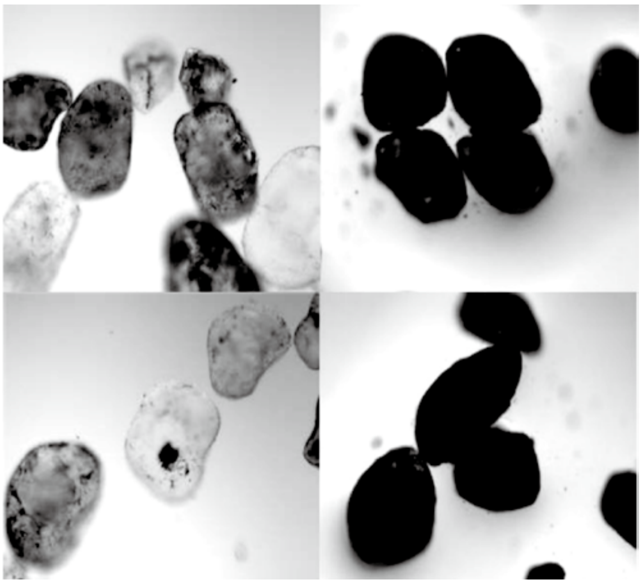


Fig. 13: Sand before AO and after AO treatment [58]

7.2 Improved heat treatment of castings using OP-AID

Almost all steel castings are given an extensive heat treatment prior to being put into service. For steel foundries energy use for heat treatment is a significant part of their overall energy use. Of that energy, up to three quarters of the energy use are spent in soak and holding times required for heat treatment [59].The heat-treatment process is energy-intensive and often requires long time holding at high temperatures that are specific to the particular alloys being produced. Therefore eliminating wasted time in the heat treatment process is beneficial from both an economic and environmental standpoint.

A great deal of wasted heat treatment time often happens while ‘waiting’ for the center of the load to reach a desired temperature. Many different techniques exist for determining when a load of castings in a heat treatment furnace is “on-heat.” These methods include a number of subjective techniques, such as matching load color with the color of the furnace, or using historical rules, such as the ‘hour-per-inch” rule that ties heat treatment furnace holding times to the section size of the castings being heat treated. However, historical heat treatment rules have proven to be overly conservative, and color matching relies on a measure of subjectivity. In order to avoid these problems, direct measurement techniques are sometimes used. Load thermocouples can be used to directly measure load temperature. However, load thermocouples are expensive, and often require extra time for the operator to install correctly, leading to losses in efficiency. In some cases, thermocouples cannot be placed within the center of cast shapes, as doing so would require destruction of the parts.

A number of non-contact control strategies have been developed to determine “on-heat” temperatures during heat treatment. These include absorption and emissivity spectroscopy, gas-flow measurement and non-contact infrared sensing. Algorithms which estimate center temperatures directly from surface temperatures requires heat transfer relationships which are sensitive to geometry. In the case of complex shaped castings extensive heat transfer FEM modeling is required to estimate center heat from surface temperature detection. These models are often dependent on a number of input variables which may or may not be available in a production environment. The models can become highly complex as reflection of energy from furnace may interfere with simplified models and not properly predict load temperatures [16]. Models which have been simplified for use in production environments often suffer when variable furnace conditions persist[59]. Emissivity and reflectivity measurements vary with metal type and temperature, and complex thermodynamic models are required to properly evaluate temperature based on these situations.

A simple and elegant solution is to make early and accurate “on-heat determinations’ by examining the rate of temperature change from external elements. This can include measurements such as the surface of the load and/or the gas flow rate into the furnace. It is expected that as the rate of change of temperature approaches zero, a steady state is reached between castings and environment, and the desired “on-heat” temperature is reached. The On-heat Prediction through Aggressive Infrared Detection, or OP-AID method was developed to assist furnace operators in determining when on-heat temperature is reached. The OP-AID method uses filtered data from an on-contact infrared load temperature sensor mounted on the furnace wall to determine when the rate of change of the surface temperature approaches zero. Equipment requirements are simple, as IR sensors are readily available, although the sensor requires a direct line-of-sight path to the loads being measured. Trial results with simple shapes are shown in Fig. 14. Operators can also set control limits around the signal to facilitate improvements in heat treatment consistency from load to load. These limits can be aggressive if cost-savings are the main objective, and/or conservative if metallurgical concerns are of the highest importance.

Table 3 demonstrates the time savings in initial trials of OP-AID with simple geometries. In all geometries, there was a large time savings over the “hour per inch “rule commonly used to insure that heat treatment loads are up to temperature. Time savings approached 25% as compared to the hour per inch rule in the solid rectangular shapes and cylindrical solid rod. In non-continuous loads, such as bundled rods, the time savings was even more pronounced as loads only required about a third of the time to reach prescribed temperatures as compared to the hour-per-inch rule. Temperature detection in IR sensors has been found to be as accurate as thermocouples; temperature differences between that which was detected by thermocouples and the IR sensor were all well within the 18°F tolerance window prescribed by the heat treatment facility.

It is clear that substantial savings and energy savings over the previous inch per hour heuristic rule is possible with low-cost sensors and simple modifications to heat treatment control practices. In the future, OP-AID and similar casting heat treatment control strategies could be effectively used to shorten heat treatment ramp-up cycle further reducing furnace fuel combustion and the associated green house gases.

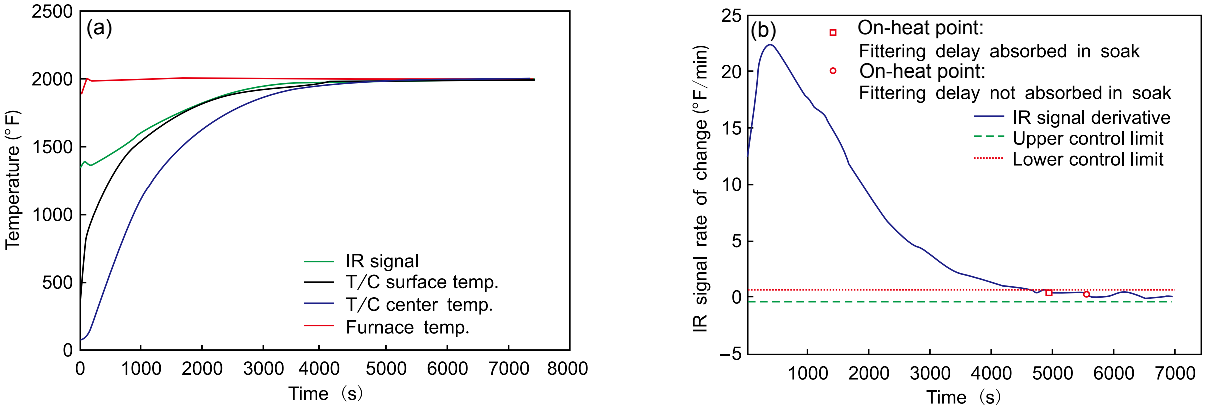


Fig. 14: OP-AID graphs showing (a) comparison of infrared sensor and actual thermocouple temperatures and (b) detection of "on-heat temperature" by determination of steady-state conditions per OP-AID

Table 3: Performance characteristics of OP-AID model [59]

	OP-AID target time (min)	"Inch/h" heuristic rule (min)	Time savings (min)	Reduction (%)
Φ 20 cm cylinder	82	240	158	66
Φ 7.6 cm bundle of 0.8 cm rods	53	90	37	41

8 Conclusions

This paper provides a broad perspective on combining lean manufacturing methods with environmental sustainability to assist foundries in remaining competitive. Two specific technologies which both improve cost and reduce environmental impact for foundries were reviewed, demonstrating that environmentally sustainability solutions can also reduce foundry operating costs. A set of proven, effective lean tools and techniques that can assist foundries in their sustainability efforts were reviewed. These tools are part of a proposed framework of key elements for foundries implementing a combined lean and green strategy for sustainable success. This framework identifies key process improvement efforts for foundries, including improving throughput, energy efficiency, innovative technology, and community partnerships. These process improvement efforts are supported by a pervasive organizational philosophy for lean / waste reduction. A review of lean/sustainability practices in the foundry industry and other industry sectors demonstrates there is a positive synergy between lean efforts and environmental sustainability. While implementing a lean manufacturing system does not lead to environmental sustainability, including environmental and other sustainability components within a lean system improves a company's ability to make continuous improvements in both cost and environmental impacts. This synergy between lean and green efforts provides the foundry industry a clear pathway and framework to become economically and environmentally sustainable.

References

[1] Dalquist S and Gutowski T. Life cycle analysis of conventional manufacturing techniques: sand casting. In: Proceedings of ASME International Mechanical Engineering Congress and R&D Exposition, Anaheim, California, USA, November 13–19, 2004: 239–243.

[2] Dalquist S and Gutowski T. Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting. In: Manufacturing Engineering and Materials Handling Engineering(IMECE2004), American Society of Mechanical Engineers, 2004: 631–641.

[3] Womack J P. The machine that changed the world: based on the Massachusetts Institute of Technology 5-million dollar 5-year study on the future of the automobile, New York: Rawson Associates, 1990.

[4] Herrmann C, Thiede S, Stehr J and Bergmann L. An environmental perspective on Lean Production. In: Manufacturing Systems and Technologies for the New Frontier: The 41st CIRP Conference on Manufacturing Systems, Tokyo, Japan, May 26–28, 2008: 83. (Publisher: Springer)

[5] Levinson W A. Henry Ford's Lean Vision: Enduring Principles from the First Ford Motor Plant, New York: Productivity Press, 2002.

[6] Lean Manufacturing and the Environment: Research on Advanced Manufacturing Systems and the Environment and Recommendations for Leveraging Better Environmental Performance, US EPA, 2003.

[7] The Lean and Environment Toolkit. US EPA, 2007.

[8] Womack J P. Lean Thinking. New York: Simon & Schuster Audio, 2003.

[9] Shingo Prize for Operational Excellence, Application Guidelines, Logan, UT: Utah State University Jon M Huntsman School of Business, 2010.

[10] Bhasin S and Burcher P. Lean viewed as a philosophy. Journal of Manufacturing Technology Management, 2006, 17: 56–72.

[11] Rothenberg S. Knowledge Content and Worker Participation in Environmental Management at NUMMI. Journal of Management Studies, 2003, 40: 1783–1802.

[12] Bergmiller G and McCright P. Lean Manufacturers' Transcendence to Green Manufacturing. In: Proceedings of the 2009 Industrial Engineering Research Conference, Miami, FL, USA, 2009.

[13] Klassen R. Plant-level environmental management orientation: the influence of management views and plant characteristics. Production and Operations Management, 2001, 10: 257–275.

[14] Keiner M. The Future of Sustainability. M. Keiner (eds), Springer, 2006.

[15] Hart S. Beyond greening: strategies for a sustainable world. Harvard Business Review, 1997, 75: 66–77.

[16] Peacock G R. A Review of Non-contact Process Temperature Measurements In Steel Manufacturing. Proceedings of the 50th Annual Conference of ISSS (International Society for the Systems Sciences), Sonoma State University, Rohnert Park, California, 2006.

[17] Daly H. Toward some operational principles of sustainable development. Ecological Economics, 1990, 2: 1–6.

[18] Goodland R. The Concept of Environmental Sustainability. Annual Review of Ecology and Systematics, 1995, 26: 1–24.

[19] ISO 14001: An uncommon Perspective: Five Public Policy Questions for Proponents of the ISO 14000 Series of New Standards for Environmental Management. Benchmark Environmental Consulting and European Environmental Bureau, Brussels, Belgium, 1996.

[20] Corbett C J and Kirsch D A. International diffusion of ISO 14000 certification. Production Operations Management, 2001, 10(3): 327–342.

[21] Melnyk S, Sroufe R and Calantone R. A model of site-specific antecedents of ISO 14001 certification. Production and Operations Management, 2003, 12: 369–385.

[22] Jasch C. The role of standardization on promoting production and evironmental management. Journal of Cleaner Production, 1995, 2: 197–199.

[23] Wall E, Weersink A and Swanton C. Agriculture and ISO 14000. Food Policy, 2001, 26: 35–48.

[24] Stapleton P S, Margaret A. Glover M A, Davis S P. Environmental Management Systems: An Implementation Guide for Small and Medium-Sized Organizations. Second Edition, NSF International, Ann Arbor, MI 48158, USA, 2001.

[25] Ball P D, Evans S, Levers A and Ellison D. Zero carbon manufacturing facility – towards integrating material, energy, and waste process flows. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2009, 223(9): 1085–1096.

[26] ISO, Guidelines for environmental auditing: general principles = Lignes directrices pour l'audit environnemental : principes généraux., Geneva: International Organization for Standardization, 1996.

[27] Walley N and Whitehead B. Its not easy being green. Harvard Business Review, 1994, 72: 46–52.

[28] Elliott E. Environmental TQM: Anatomy of a Pollution Control Program That Works! Michigan Law Review, 1994, 92: 1840–1854.

[29] Florida R. Lean and green: the move to environmentally conscious manufacturing. California Management Review, 1996, 39: 80–105.

[30] Porter M and Linde C. Green and Competitive: Ending the Stalemate. Journal of Business Administration and Policy Analysis, 1999, 73: 120–134.

[31] Klassen R. Just-in-Time Manufacturing and pollution prevention generate mutual benefits in the furniture industry. Interfaces, 2000, 30: 95–106.

[32] Warden G. Pursuing Perfection. Michigan Health & Hospitals, 2000, 38: 22–23.

[33] The Lean and Energy Toolkit, US EPA, 2007.

[34] King A A and Lenox M J. Lean and Green? An empirical examination of the relationship between lean production and environmental performance. Production and Operations Management, 2001, 10: 244–256.

[35] Bergmiller G G and McCright P R. Parallel models for lean and green operations. Proceedings of the 2009 Industrial Engineering Research Conference, Miami, FL, USA, June 2009.

[36] Bergmiller G G and McCright P R. Are Lean and Green Programs Synergistic? Proceedings of the 2009 Industrial Engineering Research Conference, Miami, FL, USA, June 2009, or http://zworc.com/site/publications_assets/AreLeanAndGreenProgramsSynergistic.pdf

[37] Simons D, Mason R and Cardiff U. Lean and green: doing more with less. ECR Journal, 2003, 3: 84–91.

[38] Simpson D F and Power D J. Use the supply relationship to develop lean and green suppliers. Supply Chain Management: An International Journal, 2005, 10: 60–68.

[39] Venkat K and Wakeland W. Is Lean Necessarily Green? Proceedings of the 50th Annual Meeting of the ISSS (International Society for the Systems Sciences), Pocklington, York, United Kingdom, 2006: 1–16.

[40] Yang C, Lin S, Chan Y and Sheu C. Mediated effect of environmental management on manufacturing competitiveness: An empirical study. International Journal of Production Economics, 2010, 123: 210–220.

[41] Rothenberg S, Pil F, and Maxwell J. Lean, green, and the quest for superior environmental performance. Production and Operations Management, 2001, 10: 228–243.

[42] Gandhi N M, Selladurai V, and Santhi P. Green productivity indexing: A practical step towards integrating environmental protection into corporate performance. International Journal of Productivity and Performance Management, 2006, 55: 594–606.

[43] McCright P R and Bergmiller G G. Techniques for Enhancing Sustainability of Industrial Operations. In: Proceedings of the IEEE Green Technology Conference, Lubbock, TX, April, 2009, or zworc.com, 2010.

[44] Tertzakian P and Hollihan K. The end of energy obesity: breaking today's energy addiction for a prosperous and secure tomorrow. Hoboken, N.J.: John Wiley & Sons, 2009.

[45] Schifo J. Organic Hazardous Air Pollutant Emission Factors For Iron Foundries. Air Quality Committee, American Foundry Society, August 2005.

[46] Rubenstein E C. Casting Environmental Governance: The Evolution of Regulatory Relationships in the Wisconsin foundry industry, 2002.

[47] Gaughran W, Burke S, and Phelan P. Intelligent manufacturing and environmental sustainability. Robotics and Computer-Integrated Manufacturing, 2007, 23: 704–711.

[48] Rother M, Shook J, and Lean Enterprise Institute. Learning to See: Value Stream Mapping to Add Value and Eliminate Muda. Brookline, MA: Lean Enterprise Institute, 2003.

[49] Joshi S. Product Environmental Life-Cycle Assessment Using Input-Output Techniques. Journal of Industrial Ecology, 1999, 3: 95–120.

[50] Walmart Corporate. Wal-Mart Unveils Packaging Scorecard to Suppliers. November 1, 2006. http://walmartstores.com/FactsNews/NewsRoom/6039.aspx.

[51] Labovitz G H and Rosansky V. The power of alignment: how great companies stay centered and accomplish extraordinary things, New York: John Wiley & Sons, 1997.

[52] Wang Y J, Cannon F S, Salama M, et al. Characterization of hydrocarbon emissions from green sand foundry core binders by analytical pyrolysis. Environmental science & technology, 2007, 41: 7922–7927.

[53] Cannon F S, Goudzwaard J, Peters J C, et al. Use of advanced oxidation technology for emissions and materials reduction at foundries. Chemical Process Pollution Prevention Towards Zero Discharge, (ed. Tapas K. Das), New York: John Wiley & Sons, 2004.

[54] Goudzwaard J, Kurtti C, Cannon J, et al. Foundry Emissions Effects with an Advanced Oxidation Blackwater System. Transactions of the American Foundry Society, 2003, 111: 1191–1211.

[55] Voigt R C, Cannon F S, and Furness J C. Use of Advanced Oxidation Systems for Cost-Effective Emissions Reductions in the Metalcasting Industry and Beyond. In: Proceedings of Green Proceeding Conference, Queensland, Australia, 2002: 369–374.

[56] Hu Y, Zhang Z, and Yang C. Measurement of hydroxyl radical production in ultrasonic aqueous solutions by a novel chemiluminescence method. Ultrasonics Sonochemistry, 2005, 15: 665–672.

[57] Fox J T, Cannon F S, Voigt R C, et al. Decreased Bond Consumption by Processing Baghouse Dust through Ultrasonic-Cavitation-Settling coupled to Advanced Oxidation. AFS Transactions, 2008, 116: 539–546.

[58] Fox J T, Cannon F S, Voigt R C, et al. Waste Green Sand to Core Sand Reclamation, Demonstration via Casting Study with Simultaneous Clay Recovery via a Novel Ultrasonic-Cavitation System. AFS Transations, 2008, 140: 523–538.

[59] Karnezos T. Improved heat treatment process control for fuel efficiency and cycle time reduction. Master's Thesis – Department of Industrial and Manufacturing Engineering, Pennsylvania State University, 2009.

The paper was presented at the 69th WFC, Hangzhou China 2010, republished in China Foundry with the authors' kind permission.