Sustainable manufacturing in SMEs: Technology options

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Abstract

Life cycle analysis currently relies on published data and disunited models to analyze a manufacturing company or industry sector. The goal and scope freeze many aspects of the analysis. Achieving material and energy flow balance is a final step, rather than an iterative one. In this paper Object process Methodology (OPM) as used as a tool to for visualizing the material and energy flow in energy intensive foundry SME (Small-to-Medium sized enterprise) domain. OPM was found viable for such technological domain specification. The paper also describes innovative technologies which help reduce the environmental impact. A number of recommendations are provided for manufacturing SMEs as well as policy makers to consider for a successful implementation of crucial sustainability goals.

Keywords: SME; manufacturing; system synergies

1. Introduction

Today's SMEs (Small-to-Medium sized Enterprises) need to address the increasing global competition, decreasing product life cycles and increasing customer demands. [1] Sustainability in manufacturing SMEs is important to achieve increased market share while reducing environmental risks and impacts while improving the environmental efficiency of manufacturing SMEs which require more financial and technical assistance when compared to OEMs (Original Equipment Manufacturers) when moving from reactive measures for the end use of products to a more proactive consideration within design and plant operation.

Green is used as a term in the literature for exploitation of energy and resource efficient production. From a descriptive standpoint, green measures and methods are added to Environmental Management System (EMS) methods and mainly executed by applying a list of measures for energy efficiency. [2]

Over the last two decades years, the literature shows emerging innovative sustainable technologies for the cast iron SME foundries.[3][4][5][6] Grey and ductile iron castings together constitute more than 70% of all cast metals. [3] Energy effective cast iron production relies upon the availability of iron and steel scrap and upon automated green sand molding systems. The metalcasting industry located in the high cost countries such as US and Europe face worldwide competition for low cost, high-grade iron and steel scrap and face stringent air quality standards. To meet these challenges, technical innovation is essential.

The paper evaluates energy and material flows for cast iron foundries to better understand the costs and environmental benefits of these innovation technologies that are currently under deployment in the industry, as well as those nearing commercialization. The technologies replacing materials that pose high volatile organic carbon emission profiles with substitute materials that are waste products from non-foundry processes that otherwise have low economic value, have also been described.

2. Potentials for Greening Foundry Technology

The A conventional iron casting facility involves: a. core-making, b. metal preparation c. pouring, cooling, shake-out and finishing. In the first step, molds are made of green sand which along with cores are used to create a cavity into which molten iron is poured. The molten iron casting solidifies into the shape of this cavity.

After the cast solidifies, the sand is reconditioned by blending with a small amount of new sand, clay, and coal; and then re-circulated. In conventional operations, after 10-20 passes through the molding system, the carbon-coated sands and clays become hydrophobic and are conventionally disposed as solid waste. For each ton of casting manufactured, the foundry must recirculate 5-10 tons of green sand. During the molten metal production, the iron and alloys are either melted in a cupola or conventional induction electric furnace. In cupolas the main source of melting iron is coke. The coke also adds carbon to the to the final alloy mixture. The process of making foundry coke is energy and emissions intensive.

Finishing the iron product requires removing the green sand and cores from the casting by vibratory 'shake out'. Parts are then shot blast and ground to produce the finished product. Parts that do not meet quality standards are recycled. For every ton of iron poured, an average mechanized foundry consumes 20-30 million BTU of energy, 250-600 pounds of silica sand and 100-200 pounds of clay and coal. [7]

The life cycle environmental model

The system diagram (SD) for the foundry model begins the modeling process by defining the process that will be modeled and placing it within the context for the model. (Fig. 1) [10] The process being modeled is the Metal Casting Life Cycle and the context includes its major inputs, the primary fuels and raw materials and material and energy inputs to the foundry; and the major output, the cast part.

To compare the resource and emission profile of existing and prospective iron casting technologies, a baseline model measuring these features was created and calibrated for an actual cupola-based iron foundry, which was then used to estimate the impact of adopting the innovative production technologies. The life cycle boundaries include major upstream activities that supply inputs to iron casting facilities. Within the foundry production floor, the model accounts for energy, materials use and environmental emissions. These metrics are tracked at each intermediate stages of melting, core making, pouring, cooling and shakeout, during production. The downstream recovery of iron is not considered because the innovative process technologies under consideration would not be affected by their adoption. The data input to this life cycle model included management reports from real foundries, publications, as well as public data sources. [8]

The major upstream cupola melting and cast iron foundry upstream activities –power production, coke making, and sand mining –provide inputs of electricity, coke, and sand respectively, requiring fuels and raw materials and generating emissions. Cupola melting and other foundry activities require melting inputs, such as ferrous metal alloys, scrap metal and natural gas. They also require process inputs, such as parts and supplies. The entire process chain-from primary fuels and materials production through the manufacturing plant gate-produces finished case iron products and potential environmental discharges. Usage data is based on 2005 management reports by foundries, which is then normalized to relative percent change offered by the innovative technologies, in order to keep the confidentiality of the participating foundries. For the unit processes other than pouring, cooling and shakeout the baseline emissions data is from EPA's AP-42 Compilation of Air Pollutant Emission Factors: Stationary Point and Area Sources, and other EPA emission documents from US EPA. [8][9][11]

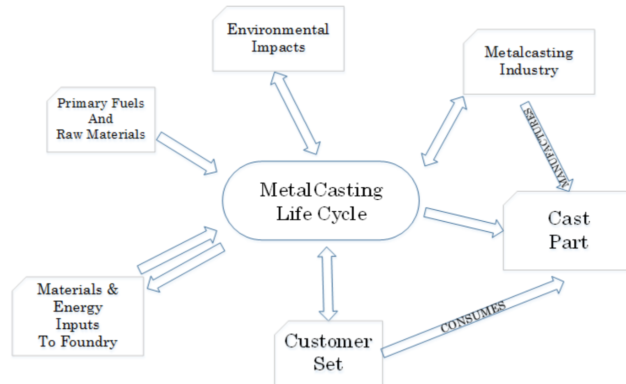


Fig. 1. High level foundry model system diagram

Cupola Melting

The inputs from cupola melting include steel and cast iron scrap, pig iron, ferroalloys, silicon and carbon. Coke generates the major energy input and provides alloy carbon. Limestone is used to flux and clean the metal of unwanted elements. Oxygen is injected into the cupola, so as to increase the melt rate and raise the cupola temperature. On the exterior of the cupola, a water jacket cools the furnace shell. Electricity powers the air blowers, water pumps and other equipment. Natural gas feeds the afterburners to complete the combustion of carbon monoxide (CO) to carbon dioxide (CO_2), and combust other carbonaceous volatiles that exit the cupola. The output of the process is molten iron and slag. For this analysis, a wet scrubber captures the particulate emissions with a sludge as a solid waste output. The CO_2 emissions reflect complete combustion of all carbon that is not in the iron product or slag.

Melt Handling

As the molten metal exits the cupola furnace, it flows into an electric holding furnace, where metallic alloys are added. The pouring ladles are heated with pre-heated with natural gas. The outputs for this process are the molten metal, which proceeds to the pouring system. Greenhouse gas emissions are computed based on the CO_2 that results from combusting natural gas.

Core making, green sand molds, pouring, cooling, shakeout and bag house dust collection

Conventional core making employs the phenolic urethane cold box process. When the core is exposed to heat from molten metal, the heat releases volatile organic carbon (VOC) emissions. Molds are conventionally made from recirculated green sand, new sand, bentonite clay, sea coal, soda ash and water. After pouring, cooling, shakeout and reprocessing, a portion of the returned greensand is discarded as solid waste. Compressed air, electricity and natural gas are used in this process. Dust is created when the sand is mixed and reconditioned; and an air exhaust system sends this dust to a bag house. In conventional systems, this baghouse dust is wasted to a landfill.

The mold is then moved to the pouring position. During molten iron exposure, the organic materials in the greensand mold and the cores experience pyrolysis and some combustion. Particulate emissions are based on participating foundry data. The VOC and greenhouse emissions data for pouring, cooling and shakeout were taken from participating foundries. The outputs from the process are cast parts and process scrap.

Metal finishing and compressed air
During metal finishing, the cast parts are shot blast, which requires electricity for equipment. The outputs are cast parts and process scrap which is later fed back into the cupola. The finishing area has a baghouse for particulate emissions that become solid waste. Air emissions are generated by the combustion of the lift truck and traced as CO_2. The participating foundries also had centralized facilities to produce compressed air, which requires electricity as input.

Upstream and off-site life cycle considerations
Fuel use and emissions in the generation of electricity is based upon data reported by US EIA. [8] The energy units used by other processes to produce electricity were apportioned to the fuel types in the profile of the participating foundry. This framework has been employed to estimate the impacts of foundry process choices. The key emissions information included in OPM model is shown in figure 2.

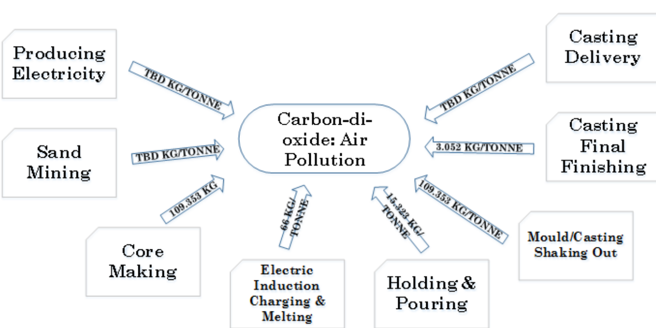


Figure 2. View of emissions information

2.1 Electric induction furnaces versus cupolas for melting iron
Since cupolas are charged with limestone, they can accommodate scrap iron and carbon sources that include high percentage of impurities. Batch electric induction furnaces use electricity for melting and require more pure (more expensive) iron and carbon sources for alloying the metal. Overall, the electric induction furnace requires 207% more fossil energy and 207% more non-fossil energy to melt iron than does a foundry cupola. [12] This higher energy demand is because of the higher relative inefficiencies in transmitting electric power and of converting heat energy to electric energy and then back to heat energy. However, the actual cost of energy for the electric induction furnace is only 9.7% higher than for the cupola. This slight increase is because the metallurgical coke used in the cupolas costs considerably more than the coal used in power plants. Utilizing anthracite fines formed into bricks in cupolas can help mitigate this large cost differential.

Operating cupolas generate local environmental impacts via air emissions. Electric induction furnaces generate fewer emissions on-site than do cupolas. One option that can be attractive to foundry personnel, therefore, is to replace cupolas with electric induction furnaces, so as to avoid these local impacts and the associated regulatory permits. This option has been adopted by several foundries in response to local air quality rules that limit the emissions from the cupola; but this is not favorable from an overall lifecycle perspective.

Specifically, replacing the cupola with an electric induction furnace, merely transfers emissions upstream to the electricity producing sector. While emissions of particulates are lower for the electric induction furnace option than for the baseline cupola option, life cycle emissions of criteria air pollution increase 150%, when electric induction furnaces are used, while also, greenhouse gas emissions are 58% higher, and emissions of volatile organic compounds (VOCs) are 88% higher. (Table 1) This is a classic example of how air pollution standards can have indirect and deleterious effects on national emissions. Operating costs for batch induction furnaces increase 1.7% relative to the cupola furnace. These findings are limited to the places relying on coal based electricity system, such as Wisconsin, and the numbers can vary for locations with lower power sector emissions and other non-coal energy sources. [9]

2.2 Coke and Seacoal Replacement Technologies
To produce foundry coke, bituminous coal must be heated to 900-1000 degrees centigrade for 28-30 hours, consuming 15-20% of raw coal's energy and releasing an equivalent amount of its carbon as green house gases and VOC's. Two innovative technologies are currently available that avoid these emissions by partially or completely replacing coke in iron foundry production. Yet another technology capitalizes on the exhausted heat from a cupola to yield a lignite-based activated carbon in-situ. This activated lignite then adsorbs VOC emissions; and the loaded lignite can then be used in green sand molds in lieu of some bituminous seacoal and as feedstock for a brick formed coke replacement.

The first of these options is to use brick formed anthracite fines as a coke replacement. There is literature available Literature shows the use of anthracite fines formed into bricks to partially replace coke and ferrosilicon. These bricks use binder material made from collagen, silicate, and other biomaterials to match the strength and energy value of coke. The anthracite fines and biomaterials used in these bricks have a limited value as a low grade fuel, or they are otherwise thrown away as waste. Also, the bricks include silicon, which is otherwise charged into the cupola so as to provide the silicon to cast iron, and to control cupola's redox level. Lumadue et al. found that these bricks have 35-40% higher BTU content per volume than coke; and they burn as fast as coke. [13] The trial at the foundry used 4 tons of these bricks formed with biomaterials, with 25% substitution of the bricks for coke during a half-day duration. The bricks remained in-position during the rough handling when charged into the cupola; and also when they descended to the tuyere windows, where temperatures reached 1550 ^{0}C (3000 ^{0}F). It is at the level of these tuyeres that the bricks rapidly burned (not before). During this brick substitution, the total carbon charged into the furnace (i.e carbon in the coke and bricks) was decreased by 6%, while maintaining a constant melt temperature, and while achieving a more favorable CO/CO_2 ratio than with mere coke; and while also maintaining a favorable olive-green slag color that indicated suitably reduced conditions for metallic iron formation. The carbon content of the iron product remained constant, while the iron also maintained acceptable levels of Si, S and other trace metals. The trial run at the foundry indicated that the iron product quality is also maintained.

The more effective energy release could effectively diminish natural gas requirements in foundries that also inject supplemental natural gas into the cupola. In this case, the life cycle analysis assumes that waste anthracite fines would be manufactured into the brick at a coal mine site; and the other ingredients will be transported at a day's drive to this site. These would include the collagen, which is a byproduct of meat processing. The anthracite bricks must be dried at 120 ^{0}C, which involves minor energy use- and considerably less than for coking coke at 900-1000 ^{0}C for 26-30 hours.

This life cycle study estimates the impact of two variation of this coke replacement strategy: 20% and 50% replacement of coke with anthracite bricks held together with biomaterial. In the light of the energy consumed when making coke, the coal-related life cycle energy potentially diminishes 0.6% when using 20% coke substitution, or 1.5% when using 50% brick substitution (Table 1). The net life cycle energy related to transportation will be unchanged by this substitution in the case of the participating foundry: the anthracite bricks travel to the coking plants in Pennsylvania; the coking process would decrease the coal's weight by 15-20%; and then the coke product would be shipped to Wisconsin. The net transportation for these two scenarios is roughly equal, when also considering that the bricks contain 10-15% of other components that would be transported at a day's drive to a brick making site in Pennsylvania. Emissions of criteria air emissions fall from 3% to almost 7.5% below baseline levels as the rate of coke replacement varies from 20 to 50%. There are also potentially significant reductions in emissions of greenhouse gases and volatile organic compounds. (Table 1)

Table 1

	Antracite fines for brick for coke (%)		**In-situ activated lignite for seacoal[3]**	**In-situ pyrolyzed bituminous coal bricks[4]**
	20%[1]	50%[2]		
Total system including upstream (+ increase, - reduction)				
Energy				
Fossil	-0.6	-1.5	-0.6	-3.0
Non-Fossil	-0.6	-1.5	-0.6	-3.0
Emissions				
Greenhouse gas	-0.4	-0.6	-0.4	-2.8
Criteria Pollutants	-3.0	-7.5	-2.9	-14.9
Particulates	-3.3	-8.3	-3.3	-3.3
VOC	-0.3	-0.7	-23	-1.3
Foundry facility (+ increase, -reduction)				
Materials				
Seacoal			-100	
Coke (as alloy)				-100
Ferro-Alloys	-5.8	-11.5		

1. Bench tests and full scale tests have been conducted 2.Bench tests have been conducted, and full scale trials planed 3.Bech tests have been conducted; and simulated full scale trials have been conducted, 4. Pilot plant testing in progress

Another innovation for iron foundries is to use the waste heat from the cupola to pyrolyze lignite coal in-situ. This produces activated carbon fines that can be blown into the exhaust ducts from pouring/cooling/shakeout; so as to absorb VOC's both in the ducts and in the bag house dust. The pyrolyzed lignite then can be re-circulated with the bag house dust back into the green sand system. There, the carbon from the lignite and the scavenged VOCs can displace some of the seacoal. The operating costs for this process are mostly electricity for material handling equipment. Notably, the energy required for pyrolyzing the lignite originates from cupola waste heat; and the associated emissions can be injected back into the cupola.

The emissions reductions occur because the activated lignite adsorbs VOCs that would otherwise be exhausted as air pollution. Full scale trials at the participating foundry confirmed the cooling and shakeout emissions reductions that could potentially be achieved by this innovation. These trials employed a commercial lignite activated carbon as a surrogate for in-situ activated lignite. This was dosed at 3.0 mg / scf into the stack gas duct. The contact time was 0.56 seconds ahead of the bag houses, and 0.32 seconds within the bag house fabric's accumulated solids. While this lignite activated carbon was used, the bag house exhaust released 0.26-0.34 lbs VOCs / ton iron (Fe) (average 0.3), whereas without this activated carbon, the exhaust averaged 0.46 lbs VOCs/ton Fe. Thus, such in-situ generated activated carbons could likewise offer roughly 23% decrease in total VOCs (Table 1).

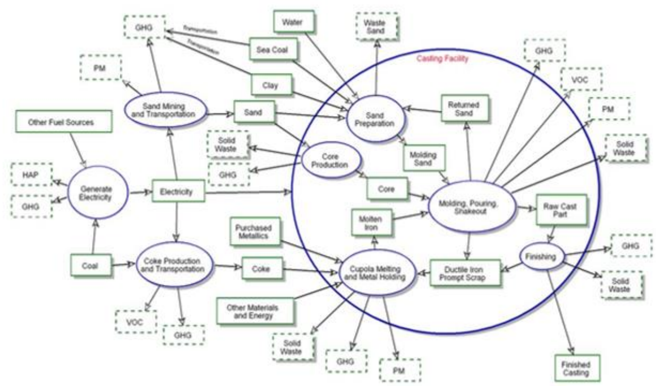
Another potential coke replacement technology is used for the waste heat from the cupola to start pyrolysis of granular bituminous coal that can be made into briquettes using the same binder materials mentioned above. The by-products of this process could be sold and/or used as fuel. Direct and indirect labor is needed for this process as it takes place within the foundry. Emission reductions are based on the reduced energy required to complete this process. VOC's are condensed as a byproduct or burned directly in the cupola. This process has been successfully demonstrated in a full scale foundry trial and can also produce material suitable to replace metallurgical coke. This process reduces the greenhouse gas emission by 2.8%. The criteria pollutant and VOC emissions improve dramatically due to the closed nature of the process.

Significant energy and material savings can occur when foundries adopt a combination of technologies such as 50% coke replacement with anthracite fine bricks held together with biomaterial; advanced oxidation-hydroacoustic cavitation for reclaiming green sand and bag house dust and collagen-alkali silicate binder with core machine technology. Some of these options are symbiotic. For example, when a water-based low-emission collagen-alkali silicate binder is used rather than phenolic urethane binder, the VOC and HAP pollution can be reduced not only during the binders first exposure to molten iron, but also during subsequent passes as the advanced oxidation process cleans the sand and clay grains. Moreover, the water-based advanced oxidation system will potentially clean a water-based binder of core sand than it will clean phenolic urethane binders.

Ny et al stated that LCA's often lack a sustainability perspective and bring about difficult trade-offs between specificity and depth, on the one hand, and comprehension and applicability, on the other. [14] They propose a "strategic life-cycle management" approach when using the currently available tools. OPM could support their approach by allowing for the iterative analysis process proposed. The scope of the foundry model can be modified to include the acquisition or production of key commodities such as pig iron, electricity, and sand. A system diagram can be imported into another model, which enables models to be aggregated or an industry or regional view of a system. All aspects of the system, including source of materials, location of that source, etc. can be included in a model. Or a model can be modified with a new process such that all the impacts of adopting a new process can be analyzed. Fig. 3 shows the input/output model of the entire iron casting process in OPM.

3. Summary and Policy Implications

The This paper tracks the material and energy flows in ductile iron castings production using conventional and advanced production techniques. Advanced oxidation systems that recycle bag house dust and sand offer environmental benefits.



foundries in the US. [3][4][5] Given the dwindling supplies and higher prices for high grade metallurgical grade coal for coke making, coke replacement could provide significant cost savings. Re-using and substituting waste materials can meet more stringent environmental standards. If the coke replacement technologies considered here were also adopted in the steel industry, the ramifications would be profound. This could significantly reduce emissions and cut reliance upon decreasing world supplies of metallurgical grade coal.

Manufacturing industry's response to pollution and resource degradation should not be limited to compliance with regulations. A broad sense of social responsibility and awareness of environmental considerations at all levels should be ensured. Towards this end, manufacturing enterprises, trade associations and labor unions could work together to establish company-wide or industry-wide policies concerning resource and environmental management and compliance with international laws in the countries that they operate in.

With limited resources at their disposal, foundry small and medium-sized enterprises often find themselves unable to afford the changes necessary to meet environmental regulations and product controls. Small-scale operations such as metalworking, casting, machine tools etc. are frequently among the worst offenders of environmental regulations across countries. Energy saving biological systems may be well suited to the requirements of SMEs for pollution control or waste disposal.

SMEs constitute the largest segment of industry in most nations, and may in some cases need financial and technical assistance from the public sector. Management and labor training can help SMEs incorporate cleaner technologies and environmental planning to their in-house production systems. Additionally, governments need to encourage collaborative efforts which bring together smaller firms in joint research and development on environmental issues, for example, combined use of waste treatment facilities.

References

[1] Min H, Zhou G. Supply Chain Modeling: Past , Present and Future, Computers and Industrial Engineering, 2002, p. 231-49.
[2] Chen D, Heyer S, Seliger G, Kjellberg T. Integrating sustainability within the factory planning process. 62nd CIRP General Assembly, HongKong, China, 2012.
[3] Cannon FS, Goudzwaard JE, Peters RW, Furness JC, Voigt RC, Kurtti CM, Andrews JH, Use of advanced oxidation technology for emissions and materials reduction at foundries, Chemical process pollution prevention towards zero discahrge, ed. Das TK, John Wiley, 2004.
[4] Milan-Segovia N, Wang YJ, Cannon FS, Voigt RC, Furness JC, Comparison of OH generation for advanced oxidation combinations applied to foundries, Ozone Science and Engineering, , vol. 29, 2007.
[5] Wang YJ, Cannon FS, Komarneni S, Voigt RC, Furness JC, Mechnisms of advanced oxidation processing on bentonite consumption reduction in foundry, Environmental Science and Technology, vol. 39, 2005.
[6] Wang YJ, Cannon FS, Li XG, A comparative analysis of hazardous air pollutant emissions of casting materials measured in analytical pyrolysis and conventional metal pouring emission tests, Environmental science and technology, vol. 45, 2011.
[7] Fox JT, Cannon FS, Brown NR, Huang H, Furness JC, Comparison of new green foundry binder with conventional foundry binders, International journal of adhesion and sdhesives, vol. 34, 2012.
[8] US Energy Information Administration, Voluntary reporting of greenhouse gas program, 2010.
[9] US Energy Information Administration, State Energy Profiles, Wisconsin, 2010.
[10] Dori D, OPM A holistic systems paradigm, Springer, 2002.
[11] US Environmental Protection Agency, Greenhouse gas inventory report, 2010.
[12] Jones AJ, The industrial ecology of the iron casting industry, MIT, 2007.
[13] Lumadue MR, Cannon FS, Brown NR, Ligning as both fuel and fusion binder in briquetted anthracite fines for foundry coke substitution, Fuel, vol. 97, 2012.
[14] Ny H, MacDonald JP, Broman G, Yamamoto R, Robuert KH. Sustainability Constraints As System Boundaries: An Approach to Making Life-Cycle Management Strategic, Journal of Industrial Ecology, 10. 1/2,2006.