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Article

Foundry Sand Source Reduction Options: Life Cycle Assessment Evaluation

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Abstract: Foundries represent a significant part of the world's economy and are a large consumer of energy and producer of solid waste. Sand-handling processes can use 5–10% of a foundry's total energy. The goal of this research was to explore source reduction and waste minimization at a foundry, using both economic and Life Cycle Assessment (LCA) techniques to compare three secondary sand-reclamation options. LCA software modeled all sand processes at a mid-sized ferrous foundry in the USA. The LCA showed all secondary reclamation technologies, while more energy intensive at the foundry, lowered life cycle environmental impacts, including GHG emissions, ecotoxicity, and human health indicators, due primarily to source reduction and corresponding reduction in transportation both from the virgin sand source and to the landfill. Varying transportation distance had a large impact on LCA results to the point where the life cycle benefit of secondary reclamation became a liability in a zero distance scenario. Varying electricity generation to favor greener sources was also examined, but proved to have minimal impact on the LCA results. This research suggests that the greatest reduction of life cycle impacts in the sand-handling processes for a foundry is to find a geographically closer source for virgin sand.

Keywords: Life Cycle Assessment (LCA); foundry sand; source reduction; transportation; secondary reclamation; microwave reclamation; thermal reclamation; sand reclamation

1. Introduction

Foundries represent a significant part of the world's economy. Metal parts made in foundries are vital to the automotive industry, in construction projects, as end products, and as parts for larger equipment. Because foundries play such an integral role, it is imperative that they operate as efficiently as possible. In the past, efficiency goals focused almost entirely on economic and production metrics, but with a greater global emphasis on sustainability, foundries need to reassess the way they view efficient operations.

The foundry industry is one of the largest consumers of energy in the United States. In 2010, ferrous foundries accounted for 5.5% of all energy use in the manufacturing sector [1]. Foundries also are responsible for 4% of all municipal solid waste produced in the United States [2]. The sand-handling processes account for 5–10% of the total energy used in a steel foundry [3] but contribute nearly all of the solid waste generated. While there has been a large number of studies focused on sustainability of foundries on a facility-wide scale [4–6], there has been a much smaller amount performed on the sand-handling processes specifically. The goal of this research is to examine the sand-handling train from a life cycle perspective and to use a Life Cycle Assessment (LCA) comparative analysis to evaluate source reduction options, using new sand-reclamation equipment from both economic and environmental viewpoints. Research was performed by using data collected from a mid-sized

steel foundry in the Midwest region of the USA. The initial goal of the research was simply waste minimization, but the scope evolved to energy and environmental sustainability as multiple source reduction options were considered.

Life Cycle Assessment (LCA) is the “compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle” [7]. LCA can be used as a tool to determine the overall environmental impact of a product, process, or service, including not only the primary components of the focus of the study, but also all upstream and downstream impacts. It is often used as a benchmarking tool to compare two competing processes by way of using a functional unit common between the two processes. The current research uses LCA as a comparison tool for the process modification of a single system, in order to highlight the changes in life cycle environmental impacts of competing technologies. This use of LCA has been applied to sectors ranging from wastewater treatment to food processing [8–11] and is believed to be appropriate for the current research.

The specific foundry and sand-handling processes described subsequently are based on information gathered from the foundry and from *The Ferrous Foundryman’s Handbook* [12]. The sand-handling steps consist of the acquisition of virgin sand, all sand processes at the foundry, and the final disposition of the sand. In the acquisition phase, virgin sand is excavated and transported to the foundry. At the foundry, the sand is used to form the molds and cores for the casting process. Then the sand enters the reclamation process and is reused or wasted at a fixed ratio called the reclaim ratio. Reclaimed sand goes through the casting process again, while wasted sand, called spent foundry sand (SFS), is sent to its end use, i.e., often a landfill; however, some reuse options are available, such as construction material [13] and soil amendments [14]. The reuse of SFS has also been shown to be much more energy efficient, as well as having less environmental impact in most categories [15], although less than 30 percent of the 10 million tons of SFS generated annually is reused in applications outside of foundries [2]. The beneficial reuse of SFS for this foundry was explored, but no viable options that were economically or regulatorily allowed in the local region. This led the researcher to explore sand-reclamation technologies as a method to reduce waste.

The goal of sand reclamation is to recondition used sand internally by cooling it, removing impurities, and sorting grains by size, for the purpose of reusing it in new mold and core production. The sand-reclamation process has primary and secondary steps. Primary reclamation is present at almost all foundries and includes shakeout, magnetic separation, and other bulk sorting processes. Secondary reclamation processing steps after the primary phase are not necessary but can be included to increase the sand-reclamation ratio. These can be categorized broadly as either mechanical or thermal in nature. Mechanical reclamation systems include a variety of methods for sand treatment. Options include systems that vibrate, shock, use air scrubbing, or other means to return sand to a usable condition for reuse in mold- and core-making. Thermal reclamation is most often accomplished through use of a high-temperature fluidized bed that is able to achieve nearly 100% reclamation rates. Microwave reclamation is an emerging technology that uses microwaves as the energy source to thermally reclaim the sand. Microwave reclamation has been shown to reach reclamation rates similar to thermal reclamation.

2. Materials and Methods

2.1. Foundry Description

The research is based on data collected in 2015–2016, from a mid-sized ferrous foundry located in the Midwest of the USA. While the foundry may have changed its process flow in the time between data collection and this report, whenever the report mentions the foundry, it is referencing the foundry as it existed in 2015, unless otherwise specified. The facility is 150,000 square feet and runs two shifts per day. The foundry pours a wide variety of steels, including corrosion-resistant high-alloy steels, heat-resistant high alloys, nickel-base alloys, and tool steels. On-site processes include mold-pouring,

weld stations, arc air stations, burning stations, finishing stations, heat treatment, tempering, quenching, and testing facilities.

The foundry sources its virgin sand from a vendor located 430 miles (692 km) away, using semi-trucks carrying between 10 and 15 tons (9–14 MT) of virgin sand per trip. This sand vendor was chosen because its sand had a specific set of superior mechanical properties ideal for the mold and core work done at the foundry.

The foundry uses a Phenolic Urethane No Bake System (PUNB) for its main mold and core operations. The mold mixture consists of virgin sand, reclaimed sand, a two-part resin, a catalyst, and iron oxide, which is mixed in a Tinker hopper before being poured into the pattern for cooling. The resin and catalyst are added to set the sand in place and give the mold tensile strength. The resin system in use is Pep Set Q I 4180 and Pep Set Q II 6180 from ASK Chemical (Dublin, OH, USA). Resin is added in a proportion of 60% first part (4180) and 40% second part (6180). The catalyst is Pep Set Catalyst, also from ASK Chemical. Iron Oxide, which is added to reduce occurrence of veining, metal penetration, and other defects [16], is purchased from Canfield & Joseph (St. Louis, MO, USA).

After the mold has been poured and cooled, it undergoes a shakeout process, to separate the steel part from the rest of the sand. After shakeout, the steel part is taken for whatever finishing processes it requires. The rest of the sand from the mold begins a process of reclamation, wherein organics, iron oxide, and other fines are removed. The remaining reclaimed sand is reused or wasted at the appropriate reclaim ratio for the next mold. It is ideal to keep the reclaim ratio as high as possible, in order to keep the cost of purchasing virgin sand low. The foundry uses an average of 80% for its reclaim ratio. This is accomplished by using two main technologies for primary reclamation: primary attrition and magnetic separation. The resulting sand is well sorted, but generally has a small amount of binder or other fines remaining on the grain surface. SFS is taken to a landfill 27 miles (43 km) from the foundry.

2.2. Source Reduction Technologies

To increase the reclaim ratio, a secondary sand-reclamation technology could be added to the existing primary reclamation processes. The secondary reclamation technologies vary widely but generally fall into either a mechanical or thermal category. For this research, three different technologies were studied and compared, using the loss on ignition (LOI) indicator. The LOI of a sand sample is a percentage difference in the weight of a sample before and after a prolonged igniting phase allows for the removal of all volatile substances. The LOI test is performed on-site at the foundry, to ensure the quality of the molds. The LOI of a virgin sand sample generally ranges from 0.3 to 1.5%, depending on the source of the sand and how it was conditioned at the quarry. Reclaimed sand should have LOIs no greater than 3% [12]. The current LOI of reclaimed sand at the foundry is approximately 1.34%. Lowering this LOI would mean the reclaimed sand could be reused more times and would result in a mold with better strength when mixed with virgin sand.

Mechanical reclamation is broadly used to describe a secondary reclamation process that cleans remaining binder from sand by friction. The friction can come from an outside force, such as a brush or grinding wheel, or more often from the sand itself, as the grains come into contact at high speed and/or pressure. Mechanical reclamation machines vary widely in size and generally achieve LOIs of 0.5–1.5% [17], comparable to virgin sand. The mechanical reclamation system modeled for this research is based on pneumatic sand reclamation technology that has been in use for many years [18]. The specific operating parameters were taken from equipment specifications and expected time of operation at the foundry [19]. The equipment is capable of processing 5 tons (4.5 MT) of sand per hour with a package power requirement of 56 kW. The operational time for the machine was balanced with reclaim sand requirements to support the expected 90% reclaim ratio described in the product literature and determined to be 6.5 h/day for a total of 1625 h/year. Its annual energy usage is 91,000 kWh.

Thermal reclamation uses high temperatures of over 800 °C to combust any remaining binder on the sand. Thermal reclamation systems are able to achieve LOIs of 0.1–0.3% [17]. In practice,

modern thermal reclamation systems can achieve sand that is as clean as virgin sand, thus supporting a 100% reuse rate; however, this is not operationally possible. Even under ideal reuse conditions, virgin sand must still be purchased to replace sand that is lost through particle fracturing, slag and other impurities, or simply as spillage during transport throughout the foundry. This waste sand either ends up in the baghouse system as fines, or in the dumpster as wasted sand. The ratio of this wasted sand depends on operating conditions, but based on gathered data from the foundry, it is estimated as 5% of the total sand used in a mold for a 95% reclamation ratio. The specific operating parameters were taken from equipment specifications and expected time of operation at the foundry [20]. The thermal system modeled in this research is based on an existing reclaim system that was scaled up to match the 5 t/h (4.5 MT/h) requirement for processing sand. The energy input for this process is 7.31 therms/t (0.8 GJ/t) of natural gas heat to achieve the required temperature. The system has a package power of 54.5 kW. To reach the desired reclamation ratio of 95%, the thermal reclamation runs for 6.85 h/day or 1712.5 h/year. The annual energy totals for thermal reclamation are 93,331 kWh/year and 62,592 therms/year (6850 GJ/year).

Microwave reclamation is an emerging technology in the foundry sand process. It uses microwaves to heat the remaining binder on the used sand, causing it to volatilize. The microwave reclamation system was modeled based on initial research and pilot testing [21], as well as further conversations with one of the researchers [22]. The results of microwave reclamation are similar in LOI to a standard thermal reclamation system, and the same 95% reclamation ratio as used for the modeled thermal system that was used for the microwave model. The model is based on a pilot project that had a throughput of 1 ton/hour (0.9 MT/h) with a package power of 35 kW used to preheat the sand to an appropriate temperature, turn the sand in a rotary drum, and generate the microwaves. The system was scaled up to match the 5 ton/hour (4.5 MT/h) requirement of the foundry for a package total of 175 kW. The operational hours of the system would match the thermal reclamation unit, but according to pilot study results, the power cycles between on and off to match the required temperature. This was found to be 50% of the time leading to an uptime of 3.43 h/day or 856.3 h/year. The annual energy use of the modeled system is 149,853 kWh/year.

2.3. System Boundaries

During our initial work with the foundry, the entire plant flow was modeled, including all metal acquisition and production. This was quickly refined into a focus on the sand transport train. This includes virgin sand extraction and transport, mold and core production, shakeout, magnetic separation, baghouse dust collection, and SFS transportation to the landfill. To this basic model, the addition of a secondary sand-reclamation step was included after magnetic separation.

The goal of adding the secondary reclamation step was to reduce the amount of virgin sand needed at the foundry. As previously discussed, the lower LOI of the secondary technologies would lead to higher reclaim ratios. In addition to less sand leaving the foundry as SFS, this would also mean less virgin sand required to replace what was lost. Initially, this was only reviewed as a good practice from an economic standpoint [23], but the research also wanted to investigate whether a decrease in the sand extraction and transport of both virgin and SFS would offset the environmental impact caused by the increased energy burden at the foundry. Previous LCA research concluded that secondary reclamation was a net negative environmental impact, but the researcher did not include a reduction in transport distance [5].

2.4. Life Cycle Assessment Development

To more fully explore the environmental impacts of implementing secondary sand-reclamation technologies, we conducted a full LCA. The goals of the LCA are to show what impact additional sand reclamation processes have on the environmental footprint of the foundry, as well as to examine if the reduction in virgin and SFS transport would have a significant impact on overall environmental

burden. To accomplish this, the LCA methodology as established in the International Organization for Standardization documents (ISOs) 14040 and 14044 was used [7,24].

The functional unit chosen for the LCA was one ton of cured molding sand. Other studies such as [4,5] used one ton of finished steel when studying foundry processes, but since this study is focused entirely on the sand-handling train, the cured mold and core sand was selected.

To keep the LCA as simple as possible while still achieving the desired goal, we selected the system boundaries in a way that excludes any process in the foundry that did not directly impact the sand-reclamation processes. The final system model (Figure 1) is the aggregate of all inputs necessary to produce molding sand. The use of imperial units is a choice that better matched the data collected. Because the results of an LCA are unitless, the inputs can be changed to any unit system, and the results will be consistent with what is reported.

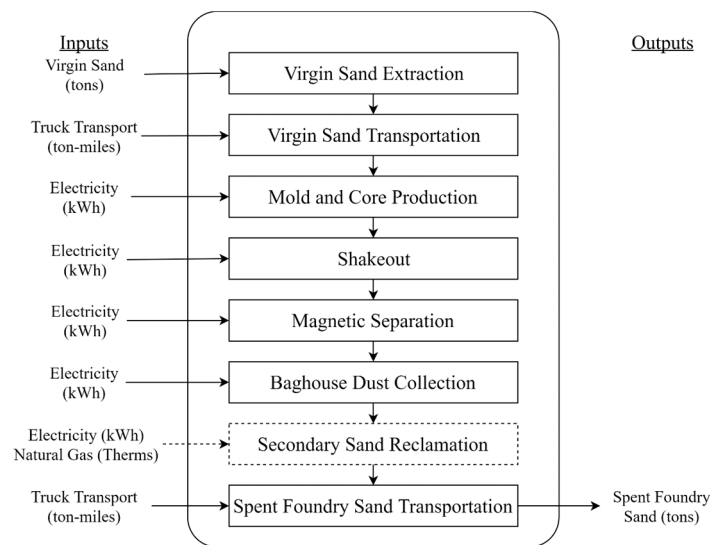


Figure 1. Aggregate Life Cycle Assessment model.

The Life Cycle Inventory (LCI) is the collection of all data, from cradle to grave, that affect the functional unit. Data for the research were collected over the course of two years, from 2015 to 2016. As much raw data as possible were collected from the foundry, at the unit-process level. Energy use for potential secondary reclamation technologies was based on manufacturer's schematics for mechanical and thermal scenarios and pilot test results for the microwave scenario. The transportation distance between the virgin sand source, the foundry, and the landfill was measured by using Google Maps. The associated diesel usage was found by using these distances and industry standards for truck fuel economy [25]. All data were collected and organized into a Microsoft Excel (2016) spreadsheet. Whenever possible, raw data were preserved "as collected", with appropriate conversions made as separate calculations. A collection of pertinent foreground data is listed in Table 1.

The Ecoinvent database version 3.3 (Ecoinvent) is one of the world's leading LCI databases built to allow for maximum consistency and transparency [26]. Ecoinvent was chosen to fill in data where no direct sampling was possible, or when the process was too complicated to sufficiently model through the use of other data. This was done mainly for background processes, such as the sand-excitation process and electricity-grid use, and to account for the larger transportation inputs and outputs.

The main tool used while conducting the LCA was Simapro (v8.2.3.0 PhD). Simapro is a widely used LCA software tool that simplifies the handling of large datasets and presenting those results. Simapro includes a number of LCI databases that can be applied based on the needs of each specific LCA. Simapro automatically keeps the Ecoinvent database up to date, to ensure the most accurate LCA results.

In the Life Cycle Impact Assessment (LCIA), the Tool for Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) methodology v2.1 [27] was used. The TRACI methodology is commonly used within the US as a way to report environmental impacts. TRACI was available as a reporting tool in Simapro and enabled all calculations and comparisons to be completed within the program.

Table 1. Life Cycle Inventory results.

Constant Inputs	Annual Usage	Usage Per Functional Unit
Electricity Input (kWh)		
Sand Mixers	46,200	5.28
Shakeout	1875	0.21
Magnetic Separator	925	0.11
Baghouse Fans	120	0.01
Diesel Usage (Gallons)		
Virgin Sand Transport	6890	0.79
Spent Sand Disposal	1820	0.21
New Process Inputs	Annual Usage	Usage Per Functional Unit
Mechanical Reclamation		
Electricity (kWh)	91,000	10.40
Thermal Reclamation		
Electricity (kWh)	93,331	10.67
Natural Gas (Therms)	62,592	7.15
Microwave Reclamation		
Electricity (kWh)	149,853	17.13

TRACI describes seven discrete impact categories that can be used to compare the magnitude of environmental impacts in each category. The impact categories are ozone depletion, climate change, acidification, eutrophication, smog formation, human health, and ecotoxicity. In Simapro, the human health impacts are reported as three subcategories: carcinogenic, non-carcinogenic, and respiratory. Aside from these main categories, resource depletion is also characterized as a separate category. When reporting results for TRACI impact categories, the magnitude of the impact is a unitless number defined as the entire environmental load produced by all production and consumption activities in the United States divided into the share of each individual.

Uncertainty is an unavoidable aspect of LCA; therefore, to ensure final transparency and utility of the results, tracking this uncertainty is an important part of the LCA process. The LCIA phase is where uncertainty must be communicated. Simapro includes an option to calculate uncertainty by using the Monte Carlo method for a single process, or as a comparison of two processes. An uncertainty analysis run on one process can show the results as a distribution for each impact category. Running the uncertainty analysis on two processes can show which process had higher or lower impacts in each category. In every case, the Monte Carlo method was run in Simapro for 1000 trials, with a confidence interval of 0.95.

Uncertainty caused by temporal, geographic, or technological gaps in the LCI data are well documented in the Ecoinvent database [28]. To compensate for this, each database entry also includes a pedigree matrix to represent data quality. This pedigree matrix enables Simapro to represent the single number values in the database as lognormal distributions. A similar approach for on-site data was performed, using the best judgment of the researcher for both expected variability and quality of the data collected.

2.5. Economic Analysis

While not the primary reason for this research, the economic viability was also analyzed. All calculated and quoted values are given in 2017 USA dollars. The cost of purchasing and transporting virgin sand was calculated given the annual usage and costs as reported by the foundry. This covered the sand itself and the shipping charges, both of which were calculated based on anticipated virgin sand requirements for all scenarios analyzed. The costs of sand-reclamation processes at the foundry include energy costs for shakeout, magnetic separation, baghouse dust collection, and secondary reclamation system, if applicable. Costs for these processes were based on machine power requirements, operational time, and utility costs as observed or reported by foundry staff. Other costs at the foundry were considered to be part of the larger foundry operations and therefore not important in this analysis. Costs for SFS transportation were based on both a fixed charge for a waste collection service and a variable charge to cover any additional SFS removal. The variable charge covered employee wages for transporting SFS in a company-owned vehicle, to and from the destination landfill, all tipping fees at the landfill, and diesel usage, all based on the anticipated volume of SFS beyond what the fixed waste management contract could provide. All of these data were based on anticipated waste of SFS, wages and rates collected from the foundry, and average regional cost of diesel fuel during 2017. New reclamation equipment quotes, as well as anticipated operations and maintenance (O&M) costs, were obtained from vendors for mechanical and thermal systems, and estimated by researchers who conducted the pilot study for the microwave system.

3. Results

3.1. LCA Results

After all of the aggregate models were created in Simapro, the LCIA was reported by using the TRACI methodology. Each model could be analyzed separately, but because the system boundaries were drawn specifically to enable comparison between the process alternatives, results from a single model would not offer useful data when viewed alone.

Results of the comparison were charted in Simapro, using the weighting and normalization factors of the TRACI methodology. These results were further refined in Microsoft Excel, to show the contribution of each input to the total model impact in each category. Each of the subsequent figures is made in a similar format. The *x*-axis shows individual impact categories corresponding to the seven categories of the TRACI methodology. In the case of human health impacts, the category is split into three parts: carcinogenic, non-carcinogenic, and respiratory. An additional category of fossil fuel depletion is also included in the output categories. The *y*-axis is a normalized unitless value representing the entire environmental impact caused by industry in the United States divided by the population. For each impact category, the comparison of each process will be slightly different. To show the difference, a cluster of four bars is shown for each impact category. These are labeled as C (current process), M (mechanical reclamation), T (thermal reclamation), and Mi (microwave reclamation). Figure 2 shows a 100% characterization of each category. The comparison was calculated by taking the maximum TRACI impact value for each impact category and using that value as the 100% value for that category. The resulting chart shows comparative details with more clarity in all impact categories, regardless of their normalized values. For this reason, characterization graphs are used for the remainder of the analysis.

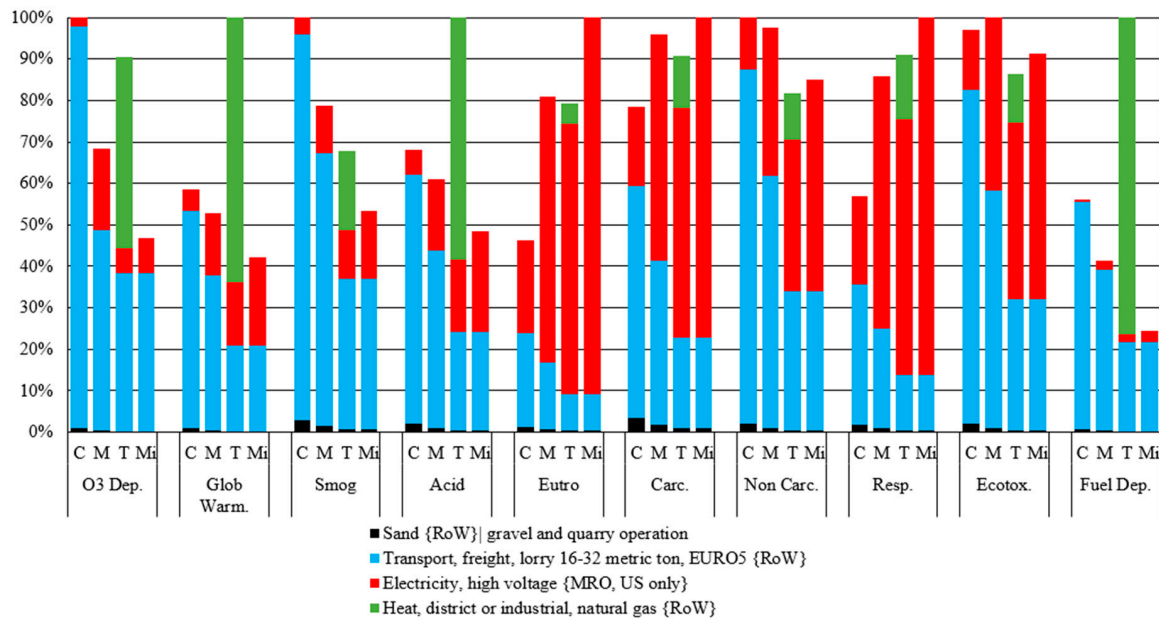


Figure 2. Comparison of four process alternatives' Tool for Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) impact characterizations.

Figure 2 aids in showing which sub-processes are most important in each impact category by normalizing each impact category by the maximum value in that category. The “Sand” sub-process includes all impacts due to the production of virgin sand. The “Transport” sub-process includes impacts caused by transporting both virgin and SFS to and from the foundry. “Electricity” includes all electrical energy inputs for all applicable processes at the foundry. “Heat” is the natural gas requirement unique to the thermal scenario. The resulting graph clearly shows which process has the greatest environmental impact in that category, as well as highlighting the contribution of each sub-process to the total impact. In ozone depletion, global warming, smog, acidification, and fuel depletion, the transportation sub-process causes the greatest portion of the impact and, in some cases, almost the entire impact. For the remaining categories (eutrophication, carcinogenic, non-carcinogenic, respiratory, and ecotoxicity), electricity also plays an important role. Natural gas impacts are shown to be primarily significant in the ozone depletion, global warming, acidification, and fuel depletion categories. The impact caused by sand excavation is negligible compared to the other inputs.

The more important question of overall environmental impact when considering each process modification can be found by looking at these results. In the impact categories identified as being primarily driven by transportation (ozone depletion, global warming, smog, acidification, and fuel depletion), the current process has the greatest impact, with the exception of processes driven by gas use, where the thermal process has a greater impact. Microwave reclamation outperforms mechanical reclamation in these categories simply because the reduction in transport distance is a greater impact reduction than the increase in electricity impact.

In the categories driven primarily by electricity (eutrophication, carcinogenic, non-carcinogenic, respiratory, and ecotoxicity), the current process tends to outperform the secondary reclamation options, but depending on the relative weight of transportation, as compared to electricity in a category, microwave, mechanical, or the current process can have the greatest impact.

3.2. Economic Analysis

The results of the cost analysis using the data explained in Section 2 are shown in Table 2.

This economic analysis, while greatly simplified when compared to the LCA, can still highlight important trends. The most apparent trend is that the total annual operating cost decreases as new reclamation technology is introduced. It is also important to note that energy-usage cost at the foundry

will increase when the equipment is added. The net decrease in annual cost can be readily explained by the reduction of virgin sand purchased. The current cost of purchasing and transporting virgin sand constitutes 73% of the total life cycle operating cost. By increasing the reclaimed sand percentage, the virgin sand requirement can be decreased by 30% in the case of mechanical reclamation, and by 65% in the case of the thermal or microwave systems. This, in turn, leads to savings in virgin sand purchase costs, virgin sand transport costs, and SFS transport and disposal costs.

Table 2. Cost comparison of current practice to three secondary reclamation technologies

Annual Expenses	Secondary Reclamation Technology			
	Current	Mechanical	Thermal	Microwave
New Equipment O&M Costs	-	\$2000	\$15,000	\$10,000
Virgin Sand Transportation	\$52,500	\$36,750	\$18,375	\$18,375
Virgin Sand Purchase	\$36,875	\$25,813	\$12,906	\$12,906
Reclamation Cost	\$2456	\$7006	\$47,807	\$9948
Landfill Surcharges	\$8297	\$3319	-	-
Landfill Transportation	\$3074	\$1230	-	-
Waste Management Service	\$19,500	\$19,500	\$19,500	\$19,500
Total	\$122,702	\$95,617	\$113,589	\$70,729
Savings from Current Practice	-	\$27,085	\$9114	\$51,973
New Equipment Purchase	-	\$300,000	\$700,000	\$500,000
Simple Payback Period (years)	-	11.1	76.8	9.6

O&M = operations and maintenance.

3.3. LCA Model Sensitivity to Transportation Distance

To study the sensitivity of the sand-handling process to distance from the foundry, we performed an analysis, using three distances, to show a wide range of possible distances. Moreover, 430 miles (692 km) was used to show the current case study and also to show an extreme distance case, 100 miles (160 km) represents a theoretical in-region source of virgin sand, and 5 miles (8 km) was chosen to represent a case where the foundry would be extremely close to the source of their virgin sand. In all cases, the distance to the landfill was not changed. New aggregate processes were created in the Simapro model by duplicating the original models and changing the transportation distance in the input data. Figure 3 shows the generated output. For each process in each impact category, there is a cluster of three bars representing the distance from the virgin sand source to the foundry: 430, 100, and 5 miles.

The reduced impact caused by choosing a nearer sand source is clearly evident in all cases. While the same basic trend of impacts associated with each technology does not change, two new trends are apparent. First is that comparing the current process at 100 miles (160 km) with the proposed technologies at 430 miles (692 km) shows that, in every case, if a closer source could be found, the current process impacts are comparable to or less than those of the proposed technologies. This indicates that if reducing environmental impacts is the primary consideration for a foundry, finding a closer source of virgin sand is more effective than purchasing expensive equipment while sourcing sand at extreme distances. The second notable trend is that, as the distance decreases, the difference between each process becomes smaller, and, in the case of the closest source, the current process performs better than any of the process modifications.

The original research also reviewed sensitivity to the electricity generation mixture by altering the regional source in the Simapro model. This was examined to show whether a greener mixture that relies more on natural gas or renewable energies for the bulk of their power instead of coal would impact the environmental comparison when reviewing the secondary reclamation technologies. It was shown that there was a small impact but negligible compared to altering the transportation distance.

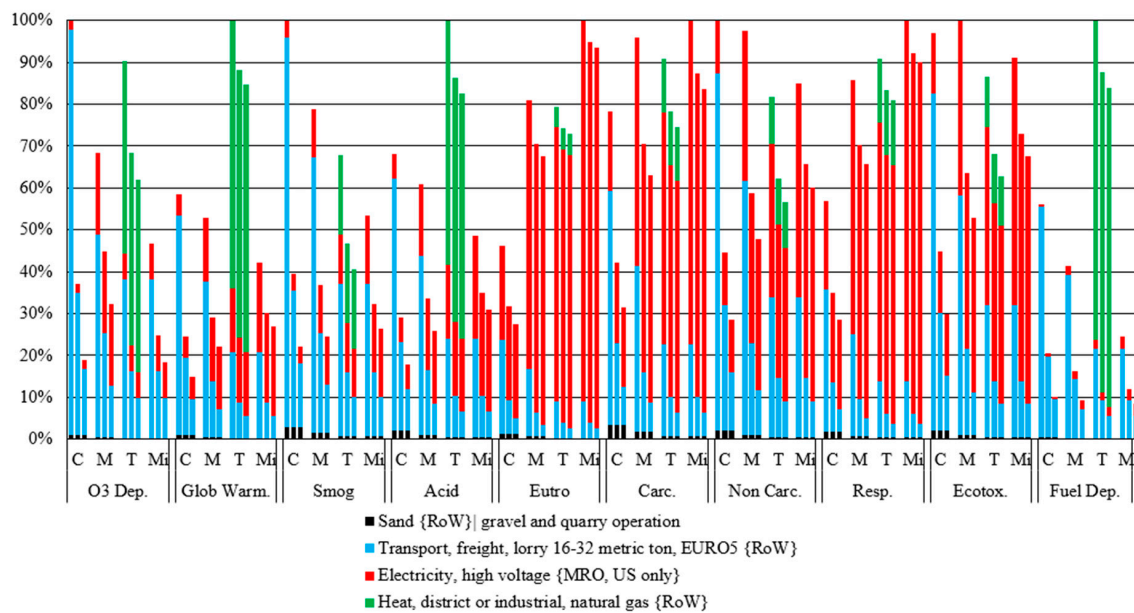


Figure 3. Process sensitivity to distance of virgin sand (430, 100, and 5 miles to source).

3.4. LCA Uncertainty

An analysis of the uncertainty of the model parameters is useful for understanding the model results. Uncertainty in this LCA model only considers the uncertainty of the environmental impacts based on the Ecoinvent database in the model. The database is transparent, and all uncertainty values are clearly documented [28]. Uncertainty exists in foreground data, but due to the wide range of data sources, quality, and variability, the inputs were chosen to be the best representative sample possible to showcase the variability and comparison between environmental impacts in a specific scenario. Uncertainty analyses were run by using the Monte Carlo function in Simapro, set at 1000 trials, with a confidence interval of 0.95. A separate analysis was performed for each individual model. In addition, comparison analyses were run for all possible scenario pairings. While all scenarios were examined, only a representative sampling is discussed.

The output of the single model uncertainty analysis in Simapro includes error distributions for each impact category, as well as a single graph showing error bars for all categories simultaneously. The uncertainty shown by this method is a good indicator of the uncertainty for each individual category in the later comparison scenarios. As shown on the 100% characterization graph of the current process (Figure 4) the outliers range from 90 to 120% for global warming, and from 40 to 310% for ozone depletion. The categories with high uncertainty, such as ozone depletion and carcinogenics, are usually due to a few specific datasets which are highly variable making an accurate estimate of a mean value quite difficult.

When Simapro compares two process models in the uncertainty analysis, each impact category for each scenario is scored separately during each iteration, and the tally of whichever scenario has the higher impact is tracked. The final result is a graph of each impact category with a sliding percentage scale to show which process had a higher percentage of higher impacts. As an example, Figure 5 shows a comparison between the current process and the mechanical reclamation process. This comparison was chosen because the pairing shows the closest results with split environmental impacts.

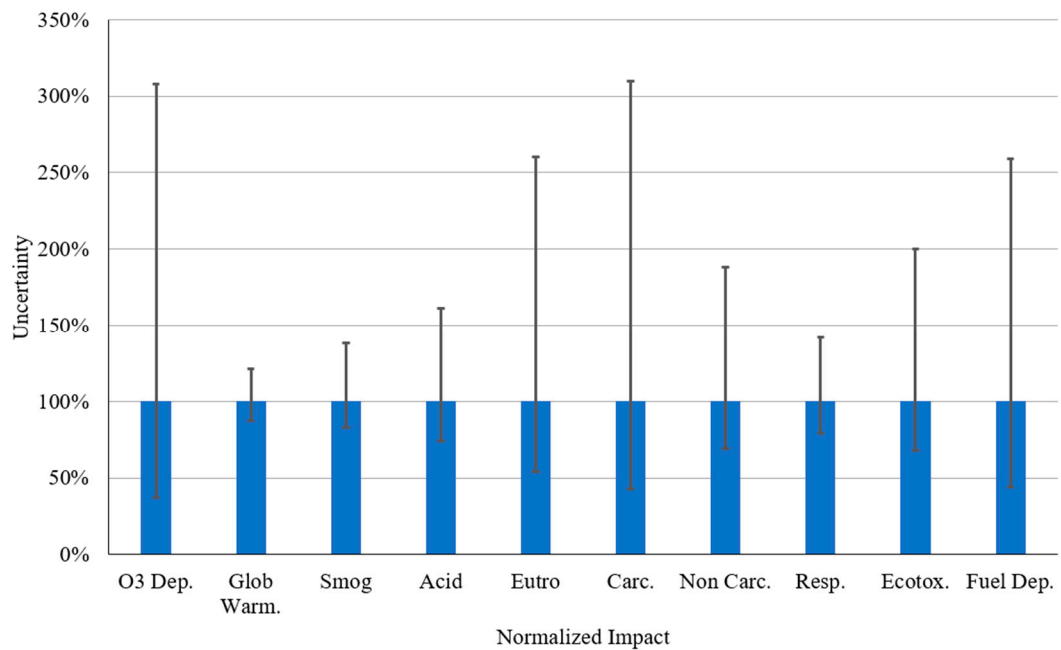


Figure 4. Current process uncertainty.

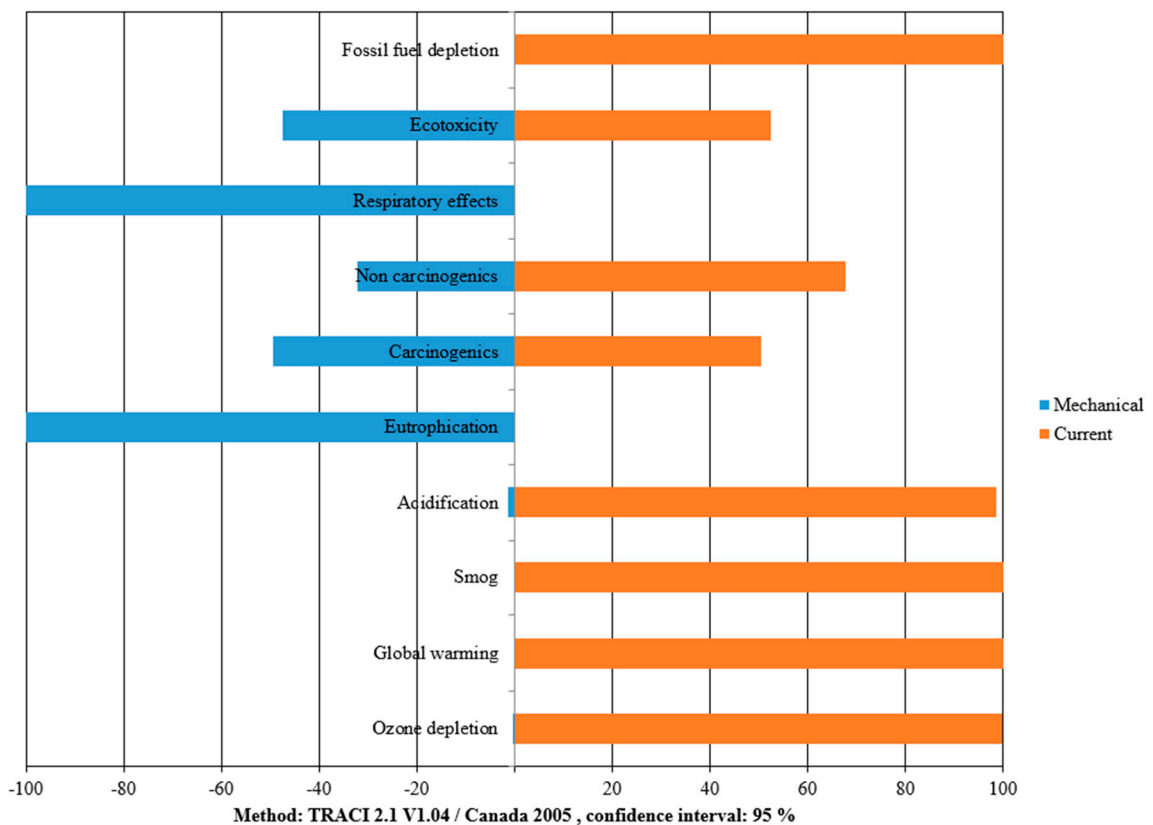


Figure 5. Comparison of current and mechanical reclamation, using the Monte Carlo method.

The right side of the graph represents the percentage of trials where the current process had greater impacts for each TRACI category. The bars showing 100% to the right mean that, for every iteration of the Monte Carlo method, the current process had a larger impact than mechanical reclamation in that category. Given what was shown in this research, most of the results of this comparison are not

surprising. The two impact areas where mechanical reclamation had a larger effect than the current process were the electricity weighted eutrophication and respiratory effects.

The three impact categories that do not have a clear leader in impact are carcinogenics, non-carcinogenics, and ecotoxicity. These three categories were also shown to have higher uncertainty when compared to some of the other categories. This graph shows that, while there is a clear difference between these categories when using the average values in the database, they are not statistically different.

When reviewing the results of the other comparisons, the trend of the data showed that, for the majority of the time, the differences shown in the LCIA are consistent and not greatly affected by the uncertainty, even if the magnitude of that difference is small. To examine this further, one additional comparison is presented here. The thermal reclamation and microwave reclamation processes generally performed the best and were often close in magnitude. Figure 6 shows this uncertainty comparison.

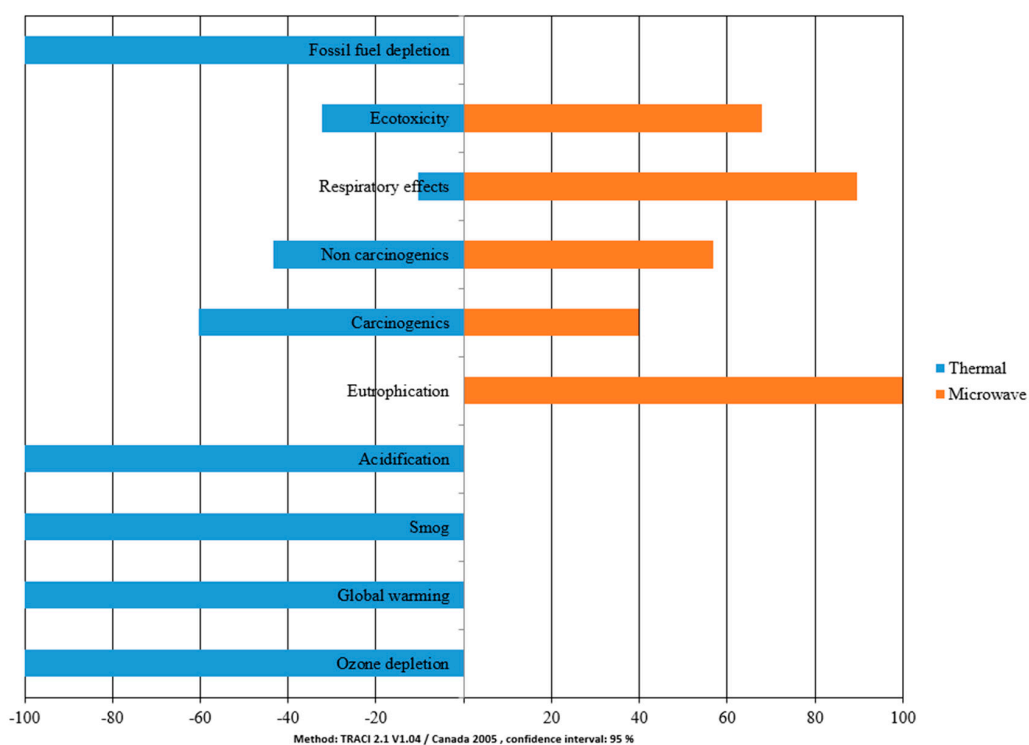


Figure 6. Comparison of thermal and microwave reclamation, using the Monte Carlo method.

For each impact category one of the two processes are clearly better or worse with possible exceptions for the Carcinogenic, Non carcinogenic, and Ecotoxicity impacts. This is a qualitative way to show that even though the processes are close in overall magnitude, there is still a clear difference between their environmental impacts. The outliers are similar to the results in Figure 5 and are not surprising because of the high uncertainty in those impact categories.

4. Discussion

It is common practice in energy-efficiency assessments to perform simple calculations based on energy consumption at the point-of-use, to find Greenhouse Gas (GHG) emissions. While GHG is a useful metric, it is important to consider other environmental impacts from a broader life cycle view. The simple energy analysis performed for this research shows one particular result for the GHG impact, but when the larger LCA picture is considered, the GHG category (global warming) is only one of several important impacts. When viewing GHG reduction results, it is important to consider whether other impact categories should be considered as well.

The impact caused by the transportation of sand from the distributor to the foundry and then the foundry to the landfill is the largest single contributor to almost every impact category in the final analysis. This can be easily explained because the distance between the foundry and the sand source, as well as the landfill, is so large. As the sensitivity analysis showed, choosing a closer virgin sand source can drastically reduce the environmental impacts of the entire sand-handling process. As previously stated, at very close distances, the main environmental impact driver is no longer transportation in many cases. When this happens, the additional energy required by the secondary reclamation processes make them perform worse, from a life cycle viewpoint, than the current process, in most impact categories. This extreme case is similar to the system modeled by Yigit [5], and similar results are found in this research.

As alternative green energy sources become more widely available, there is a better chance that foundries can purchase their electricity from a cleaner source. However, when reviewing the results of the electrical sensitivity study, we see that this would result in only a small benefit in most of the measured impact categories. Switching to a cleaner energy source may reduce impacts, but a foundry seeking to reduce its total environmental impact would be better served by looking in other areas first, such as transportation distances to both virgin sand source and landfill. A combination of both a cleaner electricity source and finding a closer virgin sand source would have the largest environmental benefit than taking either action separately.

When reviewing the economic, energy, LCA, and land-use analyses performed in this research together, we see it gives a foundry a solid set of decision-making tools when approaching a process change. Depending on the foundry's goals, values, and financial situation, the importance of each individual analysis could be weighted differently. However, this research has also shown that, in most cases, the LCA and land-use analyses generally follow the simple economic analysis that was performed.

The system boundaries in this research did not include the sand binder, catalyst, and iron oxide additives. The environmental impacts caused by the release of these chemicals is important to consider and should be included in future research. By including these, it would be possible to get a better idea of the total impacts of the sand-casting process. This would allow for comparisons between different foundries using different casting processes.

One significant limitation of the TRACI methodology for the current research is the lack of life cycle impacts due to the resource depletion of land. For this research, the necessity of including land use in the assessment was apparent from the beginning, but for other research, the need might not be as apparent. The solution used in this research only considered land area change based on conditions at the landfill and volume of SFS produced by the foundry. It was determined that, though the SFS represented a large volume proportional to other industries, the actual impact of this waste on a large landfill was very small, less than 500 ft² of landfill footprint per year; however, a true life cycle view would require a more detailed model. Future research may wish to see if land-use changes are as limited as the current model shows, by developing a better model, or by applying the TRACI model when it is developed.

5. Conclusions

Secondary reclamation is considered a BMP in modern foundries, but it is an expensive process to implement. This research shows that, in addition to an economic benefit, there is a total life cycle reduction in environmental impacts, as well as a reduction in solid waste being sent to the landfill. By showing that secondary sand reclamation can reduce environmental impacts, this research can possibly support rebate or grant applications that fall under energy efficiency, pollution prevention, or solid waste reduction. Finding available rebates or grants will also help foundries cover the large initial purchase price of secondary reclamation technology.

The current research was modeled by using landfill disposal rates that are some of the lowest in the United States, but even at this low rate, the landfill disposal costs represent between 10 and 25% of

the total life cycle sand costs. Reducing the volume of SFS being sent to the landfill by increasing the reclaim ratio is the most effective way of reducing this cost. While this is an important cost reduction in the Midwest of the United States where landfill costs are low, in dense urban areas, and in parts of Europe and Asia where disposal costs are much higher, this cost reduction would likely make secondary reclamation techniques with the highest reclaim ratios more cost efficient.

The sand-handling process is very sensitive to combined distance from the foundry to their sand source and the end point of use for the SFS. This means that the most effective way for foundries to reduce their sand-handling environmental impact is to find a sand source that is as close to their foundry as possible. It also shows that, while choosing a thermal or microwave system is always a better choice at long distances, the improvement becomes less pronounced and may disappear altogether with a closer sand source. Conversely, a foundry that must procure its sand from a distant location will benefit the most from implementing a process that will enable the highest reclaim ratio possible.

Since the initial research, the foundry where the research was performed switched from using regular foundry sand to a ceramic sand replacement. This sand replacement does not suffer from the problems of inconsistent grain size and uneven thermal expansion that regular foundry sand can, and while it is expensive, it can offer a good solution to many common problems in a foundry. While not researched directly, the use of secondary reclamation to clean the ceramic sand is likely even more important to ensure that the superior engineering qualities are maintained as the ceramic sand is continually reused. It is also the hope of the foundry that as little ceramic sand as possible be wasted, as it is expensive to replace. This would likely cut down a large portion of the transport distance and, hence, the environmental impacts. While this option was not studied, the researchers believe it would cause a net reduction in the foundry's environmental footprint.

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