Improving Process Sustainability and Profitability for a Large U.S. Gray Iron Foundry

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ABSTRACT

Energy savings and sustainability have been an important topic in many industrial processes. Limited energy resources and increasing electricity prices makes foundry processes less competitive in today's market. For foundry processes, the energy costs represent 5-7% of total sales. Most of the energy used in a foundry is directly related to melting and heat treatment operations. Integrating heat and power systems in a foundry through waste heat recovery techniques can lead to energy reutilization that improves process sustainability and profitability. In general, the average metal caster has a 2.4% pre-tax operating profit on sales. These thin profit margins are susceptible to fluctuating utility costs and energy inefficiencies. The work presented in this paper is an in-depth energy management analysis on Powersim™ to identify potential energy savings through process optimization and waste heat recovery techniques.

Initially, an energy audit of the gray iron foundry situated in Mapleton, IL was carried out. A system dynamics model of the existing foundry process has been developed on Powersim™ which investigates the complex interactions among the major energy intensive variables. This base case model was validated with the actual energy data consumption of a Caterpillar™ foundry in Mapleton, IL. Based on its results and literature review, energy saving recommendations through waste heat recovery techniques, installation of variable flow drives on fans, etc. were made which has a potential to reduce the annual energy consumption by nearly 26% or $2.6 Million.

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1. Introduction

The metal casting industry supplies finished components to a variety of industries in the manufacturing sector. These industries include automotive, railroad, aerospace, transportation, electronics, plumbing,defense, etc. In 2005, the US metal casting industry exported approximately 13.8 million tons of finished castings annually, valued in excess of $31.4 billion [1]. The average metal caster has a pre-tax operating profit of 2.4% of sales volume. Furthermore, the energy costs of the metal casting industry were approximately 5-7% of sales [2]. These values indicate that the net profit margins are sensitive to any fluctuation in commodity prices and energy usage. Therefore, it is essential to conduct the metal casting process at the optimum energy efficiency levels. Any decrease in energy efficiency of the metal casting process has a detrimental impact on the overall energy usage thereby impeding sustainability and profitability. Also, volatile energy prices and uncertainty concerning the future prices have amplified the focus on energy efficiency issues in the metal casting industry. Due to increased globalization, the manufacturing industries in general are facing stiffer competition forcing them to reduce utility costs in order to stay competitive. Increasing energy efficiency is an imperative need for the future and finding ways to optimize the energy usage is of paramount significance. Furthermore, the threat of global warming is closely associated with energy use [3]. Increasing energy efficiency possesses a potential to decrease the global warming.

Table 1: Profit margin increase of energy savings when energy costs are reduced by 35% (VA Monroe, 2000).

Original profit margin	If a plant's energy cost percentage is					
	3%	4%	5%	6%	7%	8%
	And energy costs are reduced by 35%, The profit margin will increase by					
1%	104%	139%	173%	208%	242%	277%
2%	51%	69%	86%	103%	120%	137%
5%	20%	27%	33%	40%	46%	53%
10%	9%	13%	16%	19%	22%	25%
20%	4%	6%	7%	8%	9%	11%
30%	3%	4%	5%	6%	7%	18%

According to Table 1, if a plant has 2% profit margin initially, its energy costs are 3% of total costs and it accomplishes a 35% energy saving then it has a potential to increase the profit margin by 104%. The prime assumption of 35% energy savings is not far-fetched and is achievable by implementing stringent energy saving measures [4]. It should be noted that worldwide experience has proven that mere improvement of housekeeping practices like monitoring daily energy usage, switching off energy equipment when not in use, etc. typically produces 10-15% in energy savings [4]. These are the proven results of numerous energy audits of Canadian foundries undertaken in previous years by CANMET (Canada Center for Mineral and Energy Technology) [4]. However, there are many barriers to carry out the energy efficiency measures [5]. In order to achieve energy savings it is essential to mathematically model the physics of the melting process and comprehend the complex interaction of the energy intensive variables in the system.

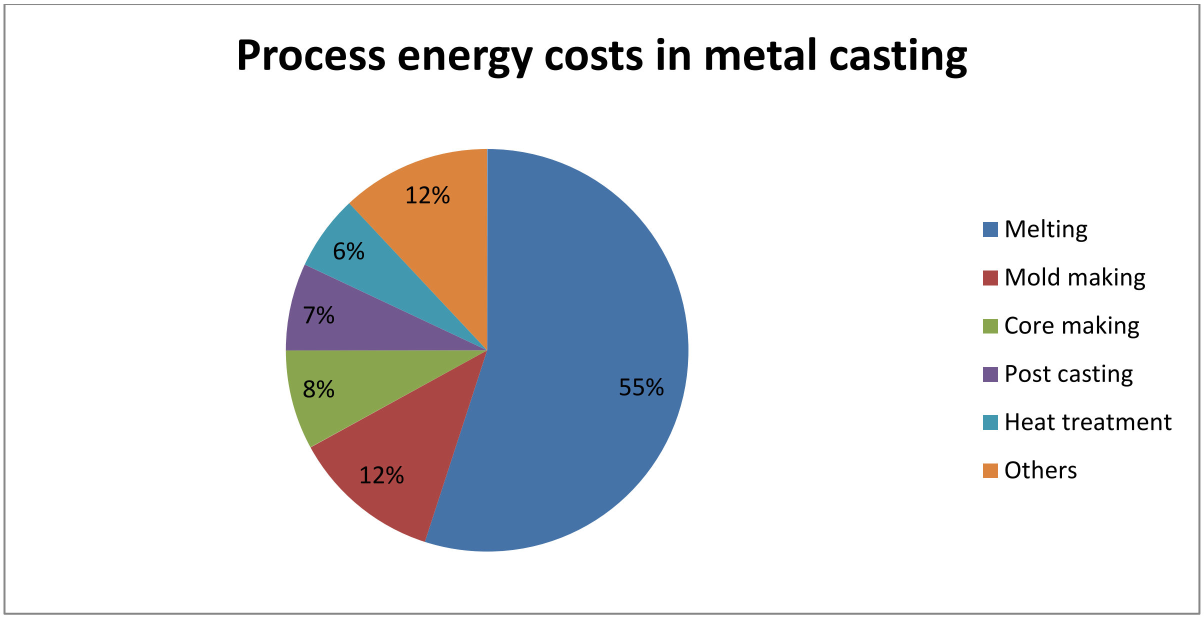

Figure 1: Process Energy costs in Metal Casting [6].

Figure 1 shows the energy cost distribution in a typical foundry [6]. According to Figure 1, melting represents more than half of the energy costs. The principal focus of this research work was to address the energy efficiency issues associated with the melting and its auxiliary processes.

2. Causal loop diagram

Causal loop diagrams(CLDs) which were developed in the 1960s were primarily used for communication of dynamic simulation models and served an integral part in the system dynamics approach. Development of CLDs is based on the concept that a causal chain of effects can be tracked through a set of mutually interacting variables which together constitute a dynamic problem. This implies that they present a hypothesis of what would happen if a certain change occurs rather than predicting what will actually take place [7].

In the initial part of this research work, specifically step 2 (shown in Figure 4), a CLD of the metal casting process encompassing all the energy intensive variables was developed. This diagram was the founding stone for the comprehensive construction of dynamic stock and flow energy model. A detailed study of these interacting variables was carried out at the Mapleton foundry to gain an insight in the energy consumption process. Loops R0, R1 and R2 represent the reinforcing (or positive feedback) loops which denotes that the increased energy consumption of the induction melter translates into increased energy losses through cooling coils, conduction, radiation respectively. Loops R3, R4, R5, R6, R7 are the balancing loops (or negative feedback) which indicates that the increase in the melter energy consumption will actually decrease the energy requirement by recapturing and recycling the waste energy. These balancing loops are self correcting in a way that they possess a potential to recapture excess melter energy. This research paper precisely addresses these negative feedback loops and attempts to model this foundry process using system dynamics. The ultimate aim of this research work is to make the process more profitable and sustainable by recapturing spent energy. The causal loop diagram shown in Figure 2 is a precursor to the energy flow model that is developed later on Powersim software.

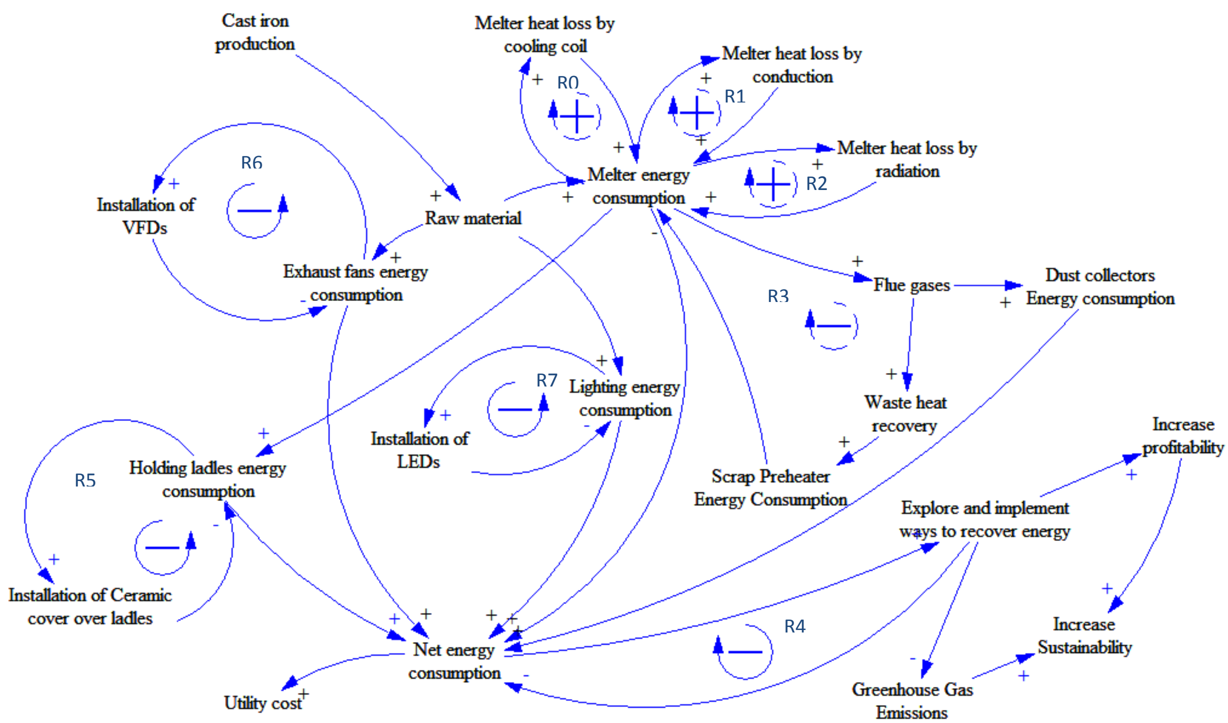

Figure 2 Causal loop diagram of energy intensive variables

3. System dynamics model of energy consumption

System dynamics (SD) is an effective tool to tackle temporal behavior of complex interacting systems. SD is a computer simulation tool used to solve complex real-world problems through system feedbacks with a focus to understand actual behavior [8]. SD is based on the concept that our world is made up of stocks, flows and feedback loops and entities in it are connected in intricate patterns[9].

In this paper an effort is made to use Powersim to map the energy flow during melting operation in a cast iron foundry. Initially, the metal casting phenomena was mathematically modeled. This mathematical model was then plugged into Powersim simulation software. A base case model of the existing process of the Mapleton foundry was subsequently developed. Figure 3 shows a snapshot of the Powersim model. Utmost care has been taken to match the actual foundry data inputs like melting time in a day, dimensions of melters, flow rates of the raw metals to melters, ambient temperature, etc to the simulated mathematical model. These data inputs have been recorded during initial data collection phase at the foundry.

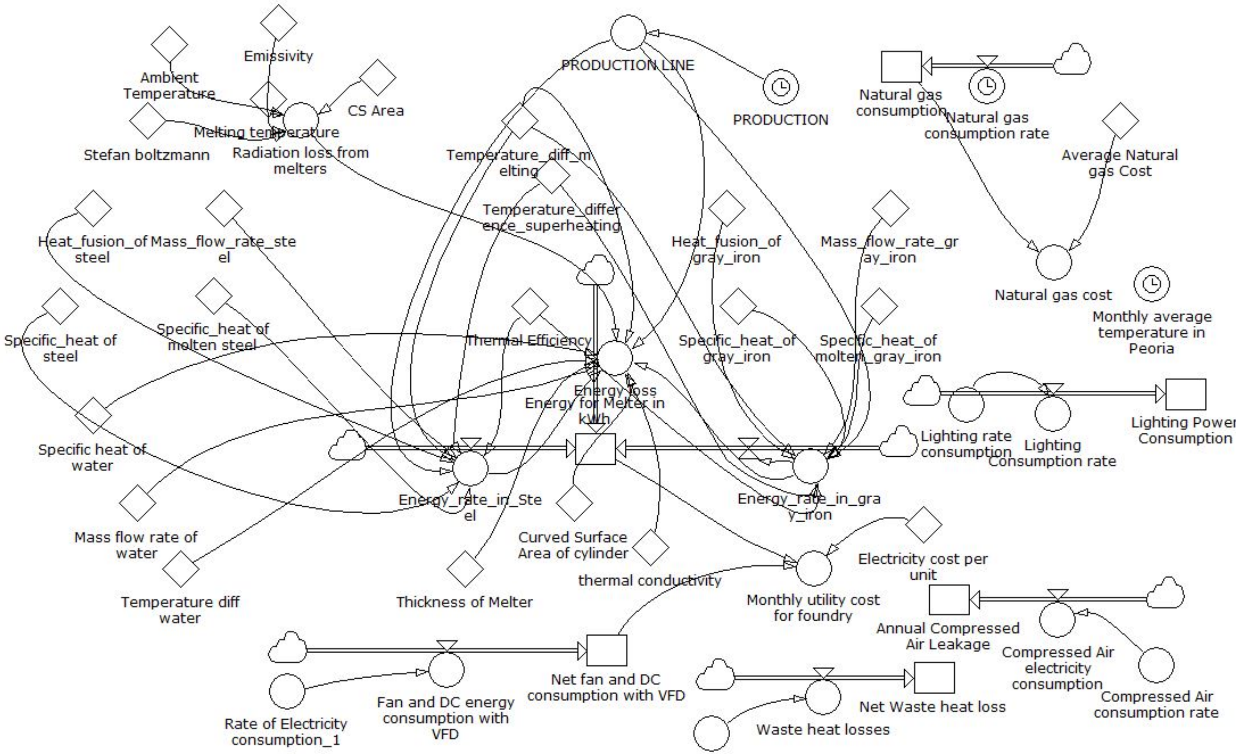

Figure 3 Snapshot of the Powersim model

4. Foundry under study

The analyzed facility is a 30 year old foundry located in Mapleton, Illinois. This facility occupies 440 acres of land and possesses approximately 20.2 acres of space. This foundry is one of the largest foundry in the US has an annual capacity of 150,000 tons of finished castings per year. The castings range in size from 7 kg liners to 10,000 kg engine blocks [10].

The melting process at the Mapleton foundry is not a continuous process, but a batch one. The batch process is carried out intermittently only during 6 hours of the day. This intermittent operation imparts the simulation model a dynamic nature. The primary aim of this research work is to identify and recommend ways to Mapleton foundry which can reduce their energy consumption and thereby increase the overall energy efficiency of the facility.

Energy usage data gathered from the foundry indicates that during 2013-14, the melting and its auxiliary processes consumed a net energy of 177.92 GWh in the form of electricity and Natural gas thereby incurring operating expenditures of $10 million on utilities alone.

4.1 Assumptions for simulation model

All the assumptions are based on the data collected at the foundry. The main assumptions for the development of the models are as follows:

(a) Two metal constituents are selected for the melting process, namely steel and gray iron with the mass flow rate ratio of 1.26. This is the same ratio that is being used in the Mapleton foundry.
(b) Melting process is assumed to occur at 2534˚F with subsequent superheating of 176˚F.
(c) Melting process is carried out only during 6 hours of the day. Specifically, between 1:00 A.M. and 7:00 A.M every day. This operation is dynamically run for the entire year.
(d) The thermal efficiency of the induction melter was assumed to be 70% [6].
(e) Energy losses such as heat loss through cooling coil, through conduction, radiation and 3% slag loss were considered [6].
(f) Based on the fan specifications provided by the Mapleton foundry professionals, energy calculations were made for 96 fans and 3 dust collectors separately and inserted into the model. To calculate energy saving with variable flow drives only those fans were considered whose power exceeded 25 HP.

5. A Step by Step approach for dynamic energy systems modelling

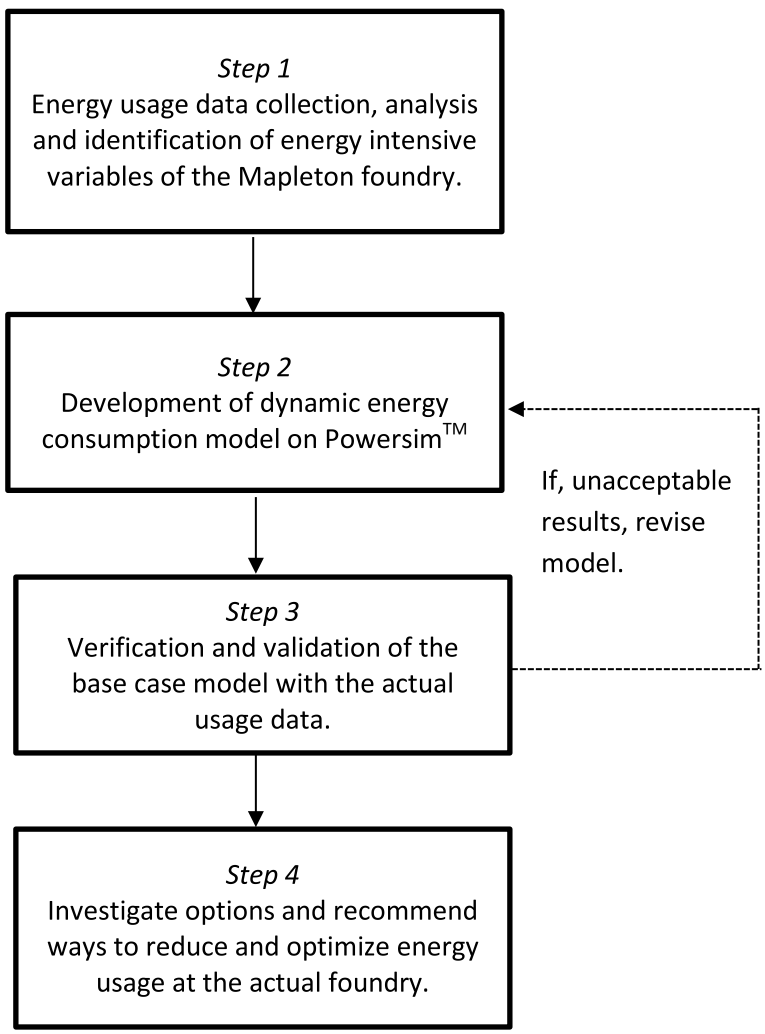

Figure 4 Step by Step Methodology adopted

This section describes the step-by-step methodology adopted for dynamic energy systems modelling. A comprehensive dynamic energy model and its analysis has been carried out using the work flow methodology illustrated in Figure 4. The outputs of the model include the annual utility cost incurred to operate the melting section in the plant.

5.1 Step 1- Energy usage data collection and analysis of the Mapleton foundry

In the first step all the available energy usage data at the facility was collected and analyzed. This data included the energy consumption by the melter, dust collectors as well as the total energy use by some of the auxiliary equipments in the melting facility. The facility records the hourly electric energy consumed by their melters and their respective dust collectors. The facility had three induction melters and three dust collectors. For the sake of simulation purposes, all the three induction melters were integrated into one. The operating time of all the melters was also recorded. The observations and suggestion of the operators and plant managers were taken into consideration and were incorporated in the simulation so as to make the model a close fit to the actual process. Based on the analyzed data, energy intensive variables were identified which would be the only variables assumed in the simulation model. Maximum effort was directed to optimize the energy usage of these variables in the subsequent steps.

5.2 Step 2- Development of the dynamic energy consumption model on Powersim

After the identification of key energy intensive variables, the melting process was mathematically modeled and simulated on commercial system dynamic software called Powersim. This model is called the base case model of the existing Mapleton process. With the consultation of Mapleton foundry professionals and literature review, maximum effort was directed to create a model of the as-is-process. Care was taken that this base case model would be an accurate representation of the existing process at Mapleton.

5.3 Step 3- Validation of the base case model with actual data

The simulated model was run for an entire year and the results were compared with the actual energy usage data of the Mapleton foundry's melting facility during the year 2013-14. The results of the simulation were also discussed and verified with the Mapleton foundry professionals to get an accurate representation of the actual process. Suggestions from the Mapleton foundry professionals were assimilated into the simulation model by revisiting step 2. Furthermore, the calculated energy consumption was also compared with the data available in the literature. Any inconsistencies, if found, were corrected by modifying the simulation parameters and mathematical equations. A critical point that needs to be noted that while running a simulation on Powersim the mathematical equations and energy flows have to be dimensionally consistent. The simulation model will fail to converge if the inserted equations are dimensionally incorrect.

5.4 Step 4- Recommend ways to reduce and optimize energy usage

With extensive literature review consisting of technical reports issued by government research institutions, [4,6] credible case studies, [4,6,11] energy saving options were explored and evaluated. This techno-feasibility review was performed with the consultation of Mapleton foundry managers and operators. Energy saving options that were explored and evaluated are as follows:

(a) Installation of waste heat recovery devices like scrap preheaters, recuperators.
(b) Installation of ceramic cover for holding ladles.
(c) Installation of variable flow drives on dust collectors and fans which consume power greater than 25 HP.
(d) Installation of light emitting diodes (LEDs) in the foundry in place of halogen bulbs.

Conservative estimations on the energy savings were made by exercising above options on the basis of thorough literature review and foundry experts' consultation.

6. Results

For the purpose of this work extensive literature review was carried out to comprehend the iron casting process, technical reports and case studies and to come up with energy saving ways, and eventually model it on Powersim. Step 3 of the workflow methodology (Figure 4) comprises of the validating the base case model with the actual energy usage data of the Mapleton foundry. Figure 5 compares the actual Mapleton foundry during 2013-14, with the estimated data predicted by the base case model. This chart suggests that that there is a mean difference of 15% from the actual values and the predicted ones. This may be due to the fact that for the case of modelling, the foundry is assumed to have an average annual capacity of 150,000 tons, whereas the actual foundry production is fluctuating and exists as a function of orders received. The foundry ramps up the production rate if the casting sales orders are high and decreases the production when the demand is weak.

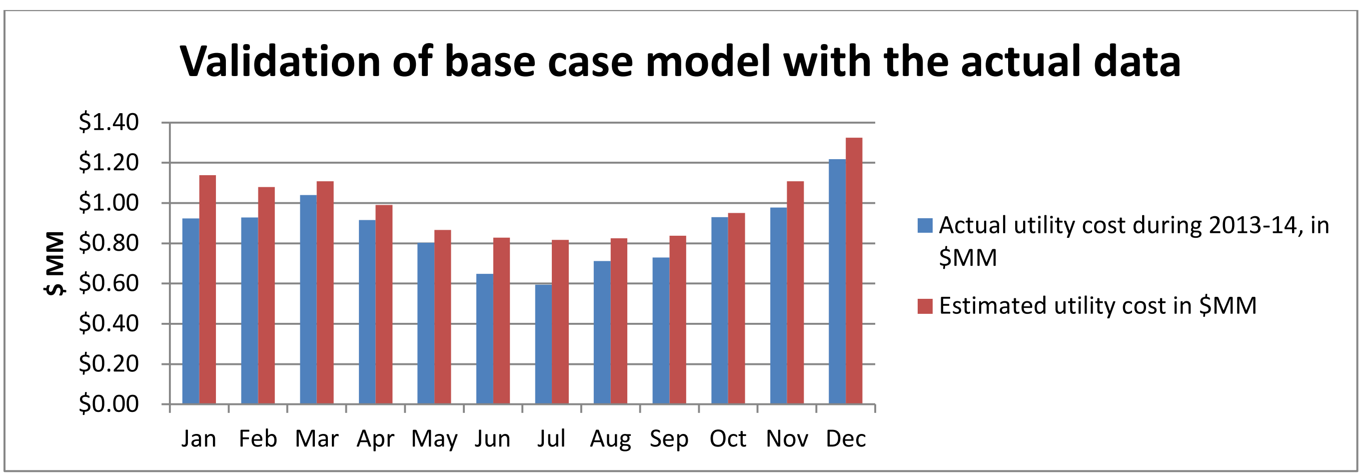

Figure 5 Validation of base case model with the actual energy usage data from Mapleton foundry.

The utility costs include the electricity usage as well as the Natural gas usage of the facility. The Mapleton foundry uses Natural gas primarily for indoor heating purpose. Futhermore, when the ambient temperature is low the Natural gas usage is high, which explains the reason behind high utility costs during October to February. Analysis of the energy usage data from the foundry also suggests that 71% of annual costs of Natural gas is spent during the 5 months from November to March. There is a strong dependency of the Natural gas usage with the actual ambient temperatures in Mapleton. Figure 6 illustrates the average monthly temperatures in Mapleton during 2013-14.

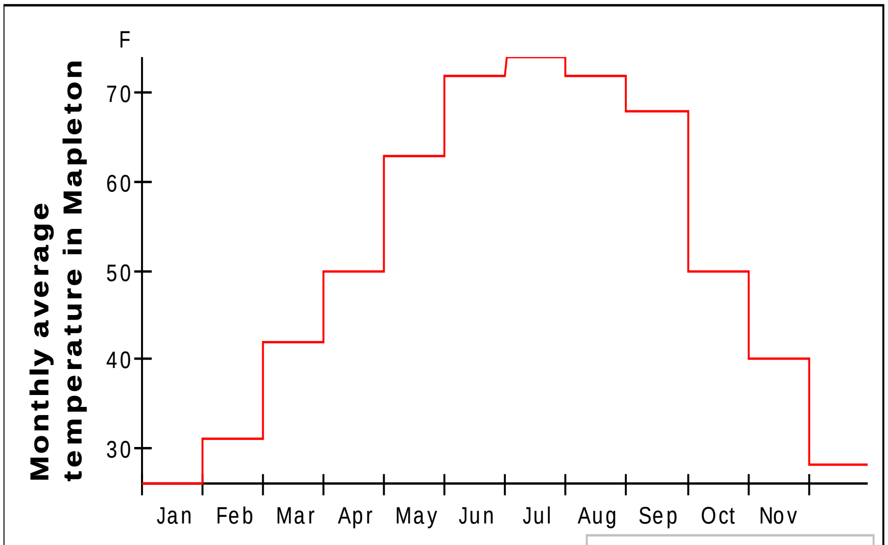

Figure 6 Average Monthly ambient temperatures in Mapleton during 2013-14 [12].

As shown in Figure 7, the slope of the natural gas cost curve is high at the beginning of the year when the temperatures are around 25^{o}F and then, subsequently the curve assumes a flat profile during summer months when the temperature is around 70^{o}F. Eventually the Natural gas cost curve reverts back to the higher slopes at the end of the year.

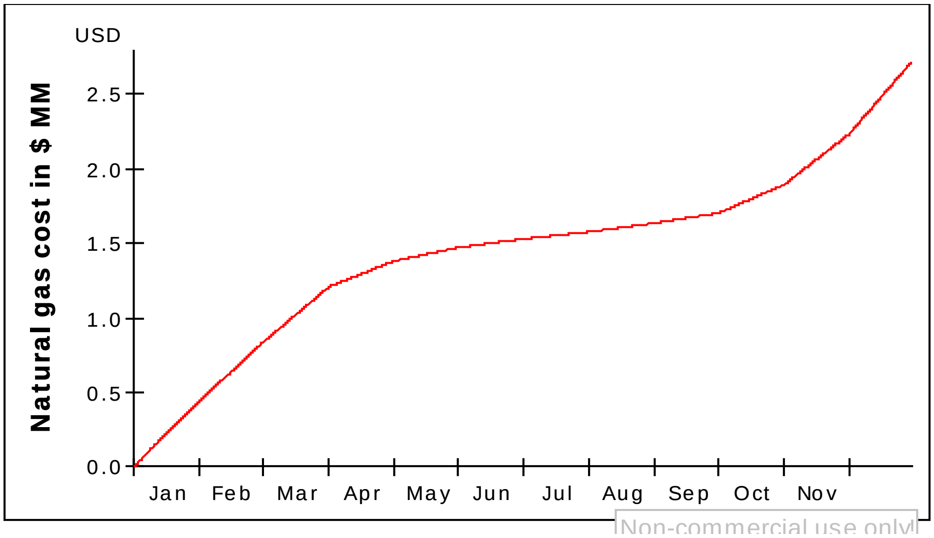

Figure 7 Actual Natural gas usage costs in the foundry during 2013-14.

This research work revealed that 96 fans and 3 dust collectors were consuming approximately $1.10 Million worth of electrical energy at nominal costs. Actual costs would be much higher taking into account the peak demand costs. According to fan affinity laws, if a fan runs on 60% of its full capacity, it will only consume 22% of the rated HP. This is because fan power consumption is directly proportional to the third power of fan speed. Our detailed analysis also showed that Mapleton foundry has a potential to reduce these costs by approximately $0.67 million by installing variable flow drives (VFDs) on these fans. The option of installing variable flow drives on these fans is capital sensitive and therefore in this analysis, VFDs were considered to be installed only on those fans exceeding rated power of 25 HP. 16 exhaust fans and 3 dust collectors were specifically analyzed for this cost saving analysis.

For a medium-sized induction furnace melting iron, the average radiation loss will be equivalent to 10-15 kWh for every minute the cover is open [4]. This melted iron is then poured into holding ladles. Installing ceramic covers on the holding ladles will significantly reduce the radiative losses from the molten iron. From our estimates, radiative losses worth $0.36 million could be reduced by installing these ceramic covers on holding ladles with a payback period of 6 months.

Table 2 Energy saving recommendations

#	Problem	Remedy	Impact	Annual savings in $MM	Annual savings in % of utility cost
1.	Compressed air leakage in foundry	Detect and seal leakage	1. Consistent air pressure, increased service life, reduced maintenance. 2. Reduction in utility costs.	0.65	6.5
2.	Wastage of heat through flue gases.	Installation of recuperators, absorption chillers, regenerators.	1. Can be used to preheat air. 2. Reduction of utility cost, emissions. 3. Improve process efficiency.	0.61	6.1
3.	Non heating of metal charge in foundry and waste heat recovery.	Scrap preheater, metal charge preheater.	1. Reduction in melting time, utility cost. 2. Reduction of moisture content of scrap. 3. Improve productivity and process efficiency.	0.53	5.3
4.	Fans, dust collectors constantly operating at full capacity.	Installation of VFDs to control speed of motors.	1. Reduction in utility cost.	0.38	3.8
5.	Radiation energy losses through ladle.	Installation of ceramic cover.	1. Reduction in radiative heat losses, utility cost.	0.36	3.6
6.	High utility costs due to halogen lighting	Install LED lights with sensors.	1. Reduction in utility costs.	0.038	0.38
Total estimated savings				2.568	25.68

Table 2 illustrates the problem along with its remedy and its impact in terms of cost. As indicated in Table 2, the Mapleton foundry has a potential to reduce its energy usage by nearly 26%. This indicates a cost saving $2.56 Million. These recommendations will make the Mapleton foundry process more profitable and sustainable.

7. Conclusion

The foundry process at Mapleton is a 30 year old process. After careful energy audit and a technical review of the process at the facility, this research work has concluded that it has great potential to reduce and optimize their utility usage. The entire goal of this research work was to make their process more profitable and sustainable. During a technical review of the process, it was found that the fans and dust collectors in the foundry were constantly being operated at 100% capacity, even when the foundry has no production taking place. Furthermore, when the mold making, core making, and sand operations were not in operation, the exhaust fans were running at full capacity. There was no process control existing over the fans and dust collectors. Simultaneously, this research work also explored the Environmental Protection Agency's (EPA) regulations for installing VFDs on dust collectors and fans. This revealed that the EPA does not have any restrictions on the operation capacity of the fans. It has restrictions only on the final pollutant emissions. EPA does not have the requirement of keeping the fans running at full capacity [13]. Subsequently, installing VFDs on fans and dust collectors will not violate any requirement with the EPA.

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