Energy consumption modelling and benchmarking in continuous galvanising lines

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Abstract: The pot hardware in continuous galvanising lines is prone to failure and needs to be replaced quite frequently which results in considerable loss of production time and high energy consumption. Galvanizing Energy Profiler and Decision Support Systems (GEPDSS) was developed to consider major energy consuming equipment in a typical hot dip continuous line which tracks the current production and energy consumption for up to three different processes. It can simulate a scenario to identify energy, cost, and productivity benefits obtained from energy savings measures and can evaluate the economic desirability of investment in new and improved pot hardware.

Keywords: energy analysis; continuous galvanising; energy consumption; steel coating; pot hardware.

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Nasr E. Alkadi has nearly 20 years of energy management experience in both USA and internationally. In May 2009, he accepted an R&D position at Oak Ridge National Laboratory, which is one of the nation's largest DOE National Energy Labs. Prior to that, he worked as a Corporate Energy Manager in General Motors Corporation where he developed unique energy management solutions to save energy in auto industry. He received a BS and MS in Mechanical Engineering from Cairo, Egypt, and a PhD in Industrial Engineering from West Virginia University. He is a Certified Energy Manager (CEM) from AEE.

1 Introduction

The steel industry accounts for 2–3% of all energy consumed in the USA (Bhave, 2003). It employs over 150,000 people in well-paying jobs and is one of the most productive, efficient and technologically advanced industries in the world. There are numerous galvanising lines in the USA. They produce galvanised steel sheet by pulling it over a roller that is submerged in a molten zinc, zinc alloy or aluminium alloy bath. Approximately half of the zinc produced worldwide is used as a coating in the galvanising of steel (and iron) for the purpose of corrosion protection (Blakley and Beck, 2004).

Table 1 summarises the net shipment of various steel products for the year 2000 and 2001. It can be observed that galvanised steel manufactured with the hot dip process in the year 2000 and 2001 accounts for 14,872,000 and 14,293,000 tons (1 ton =907.1847 kg), respectively. This ranks the production of galvanised sheet steel to be the second highest in the steel industry and thus explains the huge demand for galvanised steel products in the US market.

Table 1 US net shipment of steel mill products

	Thousands of net tons		
Steel products	*2001*	*2002*	*% Change (00–01)*
Sheets			
Hot-rolled	18,287	19,770	(7.5)
Cold-rolled	12,404	14,847	(16.5)
Sheets and strip			
Galvanised hot-dipped	14,293	14,872	(3.9)
Galvanised electrolytic	3012	3496	(13.8)
All other metallic-coated	1902	2138	(11.0)
Electrical	481	529	(9.1)
Strip			
Hot-rolled	690	869	(20.6)
Cold-rolled	1683	2262	(25.6)
Total	98,940	109,050	(9.3)

(1 ton = 907.1847 kg).

In 1994, the US steel industry consumed 2 quads (quadrillion Btu or 10^{15} Btu; 1 quad = 1.055×10^9 GJ) of energy. This study includes the losses incurred during the distribution, generation and transmission of electricity. According to Manufacturing Energy Consumption Survey (MECS), in 2002, 1.878 quads (1 quad = 1.055×10^9 GJ) of energy was consumed including the electrical losses (EERE, 2008). This is about 2% of the total domestic energy consumed in the USA and about 8% of the manufacturing energy use. Table 2 shows the energy usage in the corresponding years (EIA, 2008).

Table 2 Total energy used in steel industries

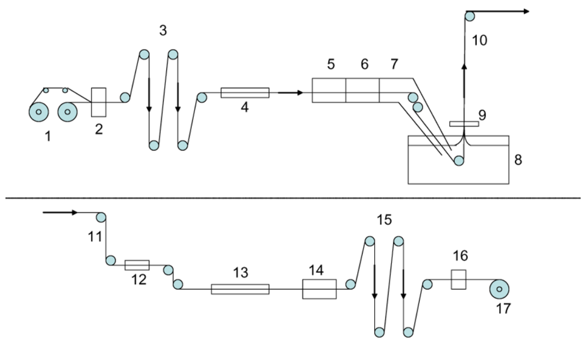
Year	*Total energy used* (*Trillion Btu's*)
1985*	2145
1988*	2355
1991*	1943
1994*	1958
1998	2003

*SIC 3312 only; (1 Trillion Btu = 1.055 × 10^6 GJ).

1.1 Continuous galvanising

A continuous galvanising line is an automated process, which uses computer controls and state-of-the-art technology. It is not labour-intensive. Also, the chemicals and metals used in the process are not deficient or restricted. The energy use is the only variable that is very important in terms of efficiency improvements. This makes energy consumption a high priority issue for survival of the facility. Figure 1 shows a flow diagram for a typical continuous galvanising line.

Figure 1 Continuous galvanising line (see online version for colours)



1 Payoff reels
2 Seam welder
3 Accumulator loop car 1
4 Degreaser
5 Non-oxidising furnace (Annealing)
6 Radiant tube section
7 Jet cooling section
8 Molten metal pot (Zn/Zn Alloy)
9 Air/gas knives
10 Up leg cooling
11 Down leg cooling
12 Galvanneal furnace
13 Online inspection
14 Chemical treatment
15 Accumulator loop car 2
16 Flying shear
17 Carrousel tension reel

The equipment listed in Figure 1 consume either electricity or natural gas. The main electricity-consuming devices are large motors used in these equipment and resistance or induction coils used for pre-melt and main zinc pot. In case of natural gas, the largest consumers are the annealing and the galvanneal furnaces. Some other equipment that are not shown in Figure 1 but consume significant energy are the plant air compressors and pot hardware pre-heaters. The galvanising facilities monitor and track various process parameters and characteristics such as furnace temperatures in zones, line speed, product mechanical properties, pot temperatures, pot chemistry and sheet steel surface quality. The product quality is critical for applications such as automotive, and extreme care is taken by the facilities to avoid product quality problems by closely monitoring and tracking product, process and system parameters using commercially available equipment. The products are manufactured in 'campaigns'. Each campaign signifies a continuous production of a product type (steel with zinc/aluminium coating) until the line is stopped either owing to attainment of production volume, failure of pot hardware, or the need to do regular maintenance on line equipment.

1.2 Need for research

The pot includes hardware submerged in the molten metal. The submerged hardware consists of a sink roll, two stabilising rolls and the structure supporting these rolls. Owing to the high temperature and corrosive nature of the molten metal in the pot, the bearings and the journal on the rolls have a short service life. Other than for maintenance issues, the most frequent cause for line stoppage is the hardware problems in the pot. The replacement or repair of the submerged hardware requires a complete stoppage of the production line. Any defect on the submerged hardware deteriorates the quality of the coating on the steel and that leads to product rejection owing to unacceptable quality. This leads to frequent replacement of the submerged hardware. In several galvanising lines, the average campaign period for a typical galvanising line is little more than two weeks owing to hardware failures.

During the shutdown period, prior to start of the next product campaign, much of the equipment needs to be kept operating. For example, the coating metal must be kept molten in the pot and the annealing furnace burners will have to be operated on low fire owing to process constraints. Air compressors and cooling towers continue to operate irrespective of production. The equipment that needs to be kept operating typically consumes about 6000 MMBtu/year (1 MMBtu = 1.055 GJ) during the shutdown period.

In addition, frequent shutdowns raise quality issues, increase scrap and generate inventory. It is not only the cost of energy that is increased but the productivity also deteriorates owing to frequent changeovers. It is important to increase campaign periods to improve productivity. For example, increasing the campaign period from the current average level to a new level of 35 days, production time loss can be reduced by 50% and the energy consumption during downtime is reduced to 2500 MMBtu/year (1 MMBtu = 1.055 GJ). Assuming a production rate of 40 tons (1 ton = 907.1847 kg) per hour, an annual increase of 8000 tons (1 ton = 907.1847 kg) can be achieved in addition to 3500 MMBtu (1 MMBtu = 1.055 GJ) of energy savings.

Productivity drives the hot dip continuous galvanising line industry. Tons (1 ton = 907.1847 kg) of finished steel produced per hour is monitored carefully. Methodologies suggesting any increment in productivity are appreciated by the manufacturer. Improvement in productivity and quality of product has always been a prime focus for any industry especially when it comes to a technology-driven, hi-tech, highly competitive industry such as the steel industry. Projects focusing on energy efficiency also impact the productivity of the industry. Hence, it is necessary to develop a model, which will tie the annual production and energy consumption together and provide value for energy per unit production. Various tools are available to measure production and energy consumption independently but none of them consider the joint effect of these two parameters together and develop the overall energy and cost scenario. Hence, there was the need for a tool (GEPDSS) that will allow simulation and sensitivity analysis.

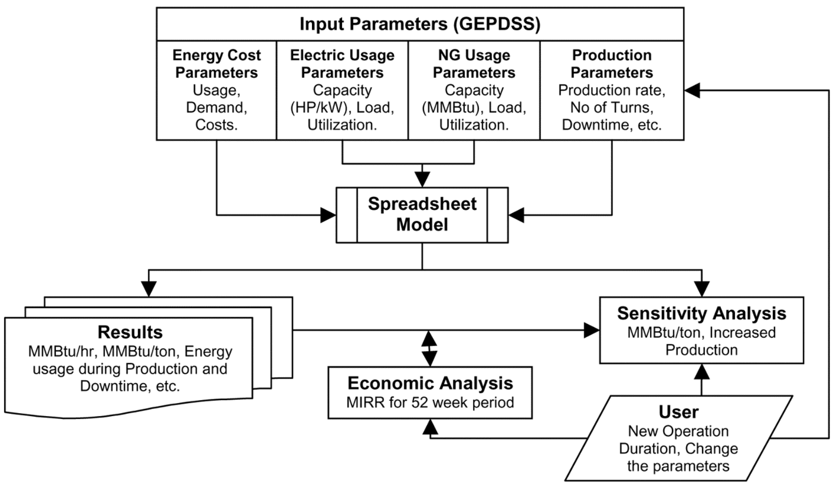
1.2.1 Necessity for sensitivity analysis

Once the energy consumption per unit production is obtained, the next step is to identify the opportunities for energy conservation. The Department Of Energy (DOE) provides several tools and information to assist in the field of energy conservation, efficiency improvement and waste minimisation. One can calculate and enter the savings obtained as a result of implementing one or more of these techniques to obtain the revised energy consumption. A simple comparison of the new energy consumption with the existing consumption or with a benchmark will help to filter out the most beneficial alterations that need to be made to the system. With the help of this model, it can be easy to obtain the management approval for funds needed to implement the changes. Sensitivity analysis can provide changes in energy consumption and production within minutes without any physical change to the existing system. If one wishes to obtain the energy benefits as a result of application of a better hardware material, the material needs to be tested only for a period of few weeks and then the results can be extrapolated to obtain the annual savings.

1.2.2 Galvanising Energy Profiler Decision-Support System (GEPDSS)

A tool was required to validate the energy savings that resulted from the technological innovations arising from the US DOE-funded projects. Comparing the previous and current energy bills would help to estimate the impact of energy savings. Sometimes, it was not practical, as it may take years for the materials to get established in the market and lead to results. Hence, a computer model was required to approximate the impact of the new hardware materials on the energy consumption and energy intensity of the galvanising lines. Figure 2 shows a system diagram of the proposed Decision-Support System (DSS).

Figure 2 System diagram (conversion factors: 1 MMBtu = 1.055 GJ)



1.2.3 Developing the Decision-Support System

The challenge was to identify a basis for comparison and quantification of energy consumption. Several options were considered including energy consumed per hour, per ton (1 ton = 907.1847 kg) and per unit area of steel galvanised. The common unit of measurement for the galvanising industry was tons (1 ton = 907.1847 kg) of galvanised sheet steel produced. The facilities were also interested in learning about any increase in production along with the savings in energy. The research objectives can be summarised as to create a model that ties all energy points on a continuous galvanising line with respect to the production and rejection rates, enabling sensitivity analysis and providing decision-making information for managers and researchers.

2 Literature review

2.1 Energy measurement and monitoring

The modern machinery is very well equipped with controls and metres to administer the required amount of energy based on demand and provide the current energy consumption data for the equipment. Several energy management tools such as MotorMaster+, AIRMaster+, 3E Plus and PHAST (US DOE BestPractices software's) are provided by the US DOE. All these software tools need data input measured from various sensors. The result is in terms of the energy consumption, energy loss, efficiency measurements and economics for particular equipment like compressors or boilers.

Blakey and Beck (2004) have developed a dimensionless equation-demonstrating method for improving furnace efficiency. They showed that the current method of burner turndown to reduce energy consumption worsens the thermal efficiency of the furnace (bath furnace), especially at low levels of capacity utilisation. The research focused on energy consumption of natural gas fired galvanising bath furnace. This was the first approach, using specific energy consumption from the demand and supply point of view, to describe thermal efficiency. The equations developed are used to compare furnaces of different design and fuel types (Blakley and Beck, 2004). Yoshitani and Hasegawa (1998) developed a mathematical model to control the strip temperature in continuous annealing furnace. The model previews the approaching set-up change, change of strip size or reference temperature, and optimises the line speed and strip temperature profile.

2.2 Development in galvanising pot hardware

In recent years, research has been conducted to evaluate the performance of materials in galvanising baths to identify 'high performance' pot hardware materials (Chang et al., 2001). Attempts are being made to develop materials that can withstand the high temperature and corrosive environment of the zinc pot and provide a prolonged service life. Research has progressed on two such projects supported by the US DOE, Industrial Technologies Programme. The projects are "*Development of Improved Materials for Continuous Steel Hot-Dipping Processes.*" *2001–2005*, and "*Multifunctional Metallic and Refractory Materials for Energy Efficient Handling of Molten Metals*" *2004–2008.* The research group consists of West Virginia University Research Corporation, University of Missouri-Rolla, Secat, Oak Ridge National Laboratory, Energy Industries of Ohio and over 23 industrial partners. The benefits resulting from the latter project were calculated using the Government Performance and Results Act 1993 (GPRA) spreadsheet. The energy savings projected using the GPRA spreadsheet is summarised in Table 3. This analysis was done for the project titled, Multifunctional Metallic and Refractory Materials for Energy Efficient Handling of Molten Metals.

Table 3 Energy savings for IMF project calculated by GPRA spreadsheet

Impact by year	*2010*	*2015*	*2020*	*2025*
1% Savings (Trillions of BTU)	0.28	2.3	9.99	16.1
5% Savings (Trillions of BTU)	1.1	9.02	39.19	63.21

(1 Trillion Btu = 1.055×10^6 GJ).

These savings are calculated by subtracting the energy used by primary production sector from the total energy used by the industry. It included the energy consumed by three industrial sectors namely aluminium, steel and metal casting. The calculations to get the energy associated with the three industries that will be impacted by the ongoing research are given here.

Aluminium:

Total Energy used by the industry – Energy used by primary production sector

$= (4 \times 10^{14} - 1.747 \times 10^{14})$

$= 2.253 \times 10^{14}$ BTU

Steel:

Total Energy used by the industry – Energy used by primary production sector

$= (1.8 \times 10^{15} - 9.0 \times 10^{14})$

$= 9.0 \times 10^{14}$ BTU

Metal Casting: (energy associated with ladles, troughs, etc., and assumed as ~20% of total value)

Energy associated with molten metal containment, transfer and handling-related functions

$= (0.2 \times 2.43 \times 10^{15})$

$= 4.86 \times 10^{14}$ BTU

(1 BTU = 1.055×10^3 J)

These savings are obtained from energy associated with molten metal containment and transfer and handling-related functions. The total energy usage for these industries is 1.6113×10^{14} BTU (1 BTU = 1.055×10^3 J). It may be noted that even a small reduction in the energy intensity in these industries will lead to significant energy savings. Total production for the aluminium, steel and metal casting industries is approximately 4109 and 14 million metric tons (1 metric ton = 1000 kg), respectively, in the USA (EIA, 2008).

The DOE has sponsored several research projects in the field of material science and metallurgy. These projects concentrate on development of new materials and technology, which can realise energy savings and reduce CO_2 emissions. A modified zinc pot bearing design was proposed for increased bearing life (Loth, 2004). Different bearing materials were tested using a small-scale tester developed by the Department of Mechanical and Aerospace Engineering (MAE) at West Virginia University (WVU). The results were used for empirical wear rate modelling of zinc pot bearing material (Snider, 2002). On the basis of the discussion with different steel industries, a coating line may incur an economic loss as high as $500,000/year owing to reduction in productivity as a result of bearing failure. Corrosion tests for various hardware materials in liquid metal bath have been carried out by Oak Ridge National Laboratory (ORNL). Since 2001, a more fundamental approach to the improvement of pot hardware materials and designs, aimed at creating an entirely new class of pot hardware materials, has been underway in a cooperative programme co-funded by US Department of Energy (US DOE) with a total budget of $4.6 million (Barbero et al., 2004). Parthasarathy (2003) has done research to discover the causes of hardware wear and tear in a liquid metal bath under conditions similar to those in galvanising facilities. Zhang and Tang (2003) have done experiments to study the reactions of various materials with a galvanising bath and concluded that Co- and Fe-based super alloys and cermets coatings react with Zn-Al bath reducing bearing life.

2.3 Development in galvanising bath management

Extensive research has been carried out and is ongoing in the area of galvanising bath chemistry. Understanding the reactions, its relation with the temperature, composition and metallurgy is the primary area where the International Lead Zinc Research Organisation's (ILZRO) efforts are focused. The galvanising bath itself is perhaps the least understood component of any given galvanising line, particularly with regard to the chemistry of the contained zinc alloy (Tang et al., 1998). The zinc, iron and aluminium crystallographic structure and the properties of intermetallic compounds have been studied extensively (Chen et al., 1990). The flow of the molten metal and its behaviour during functioning of the line is modelled (Pare et al., 1995). Sensors are developed that are capable of providing accurate bath composition and temperature (Qiang et al., 1997). Computer programmes for bath managements have been developed; one of them is DEAL™ – Determining Effective Aluminium, which was developed on the fundamentals of thermodynamics (Tang et al., 1995). MAP™ – Modelling Aluminium Pickup is another computer tool that calculates the amount of Al picked up in the interface and the total amount of Al in the coating (Tang et al., 1998). Ajersch et al. (2004) performed a numerical analysis to simulate the velocity and temperature fields in an industrial galvanising bath for the continuous coating of steel strip. The simulations allow visualisation of regions of varying velocity and temperature fields.

To the best of the authors' knowledge, no source is available at present to compute the amount of energy consumed to produce coated sheet steel by continuous galvanising process. Even though there is a great potential for energy conservation opportunities in this arena, there is no commercial tool available to measure the existing energy consumption and no established benchmark for comparison.

3 Research approach

3.1 Studying the continuous galvanising process

Initial visits were conducted in leading galvanising facilities. The entire process and the basics of the continuous galvanising process were studied thoroughly. A list of all the common equipment was made. The typical characteristics of the pot and furnace are shown in Tables 4 and 5, respectively. The energy-intensive equipment and energy consumption points were noted. Figure 3 summarises the research approach.

Table 4 General characteristics of the pot

Description	*Value*	*Units**
Pot parameters		
Length × width × height	10 × 7 × 10	ft × ft × ft
Zinc bath temperature	860	°F
Ambient temperature	90	°F
Emissivity	0.5	N/A
Thermal conductivity of pot material	20	Btu/(hr.ft^2.F)
Thermal conductivity of insulation material	0.55	Btu/(hr.ft^2.F)
Thickness of strip	0.0016	ft
Width of the strip	4	ft
Density of the strip	490	lb/ft^3
Line speed	492	ft/min
Specific heat capacity of strip	0.12	Btu/lb-F
Strip temperature at entry	869	°F
Strip temperature at exit	860	°F
Sink roll details		
Diameter of sink roll	2	ft
Length of sink roll	8	ft
Sink roll material	Stainless steel 316L	N/A
Specific heat capacity if sink roll material	0.1194	Btu/lb-F
Number of times sink roll is changed per campaign	1	N/A
Density of sink roll material	499.44	lb/ft^3
Depth of sink roll from molten metal surface	2	ft
Stabilising roll details		
Diameter of stabilising roll	3	ft
Length of stabilising roll	8	ft
Stabilising roll material	Stainless steel 316L	N/A
Specific heat capacity if stabilising roll material	0.1194	Btu/lb-F
Number of times stabilising roll is changed per campaign	1	N/A
Density of stabilising roll material	499.44	lb/ft^3

Table 4 General characteristics of the pot (continued)

Description	*Value*	*Units**
Main pot		
Number of grid	1	N/A
Capacity	1600	kW
Pre-melt		
Number of grid	2	N/A
Capacity	400	kW
Ingot		
Estimated amount of Zinc added	1800	lbs/h
Estimated amount of Al-Zn alloy added	2500	lbs/h
Amount of Zinc in Pot	312,018	lbs

*(Conversion factors: 1 m = 3.2808 ft.; K = (459.67 + F)/1.8; 1 W/m^2-K = 0.1761 Btu/(hr.ft^2.F); 1 lb/ft^3 = 16.0185 kg/m^3; 1 J/kg-K = 0.0002 Btu/lb-F; 1 kg = 2.2046 lbs).

Table 5 General characteristics of the furnace

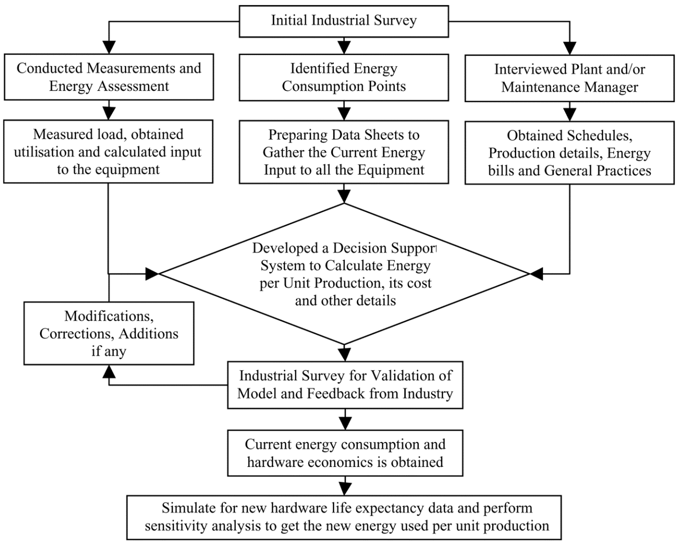
Description	*Value*	*Units**
Name of the furnace	CGL	N/A
Name of the zone	NOF	N/A
No. of burners	18	N/A
Burner rating	2	MMBtu/h
Zone temperature	2192	°F
Ambient temperature	70	°F
Length of the zone	118	ft
Width of the zone	8	ft
Height of the zone	7	ft
Outer surface temperature of the wall	400	°F
Furnace wall material	Steel	N/A
Thermal conductivity of the wall material	20	Btu/hr.ft.F
Thickness of wall material	6	inches
Insulation material 1	Refractory Brick	N/A
Thermal conductivity – material 1	1.4	Btu/hr.ft.F
Thickness – material 1	10	inches
Insulation material 2	nil	N/A
Thermal conductivity – material 2	1.6	Btu/hr.ft.F
Thickness – material 2	10	inches
Insulation material 3	nil	N/A
Thermal conductivity – material 3	1	Btu/hr.ft.F
Thickness – material 3	9	inches
Component material	Steel SAE1006	N/A
Mass	1000	lbs

Table 5 General characteristics of the furnace (continued)

Description	*Value*	*Units**
Specific heat capacity	0.115	Btu/lb-F
Initial zone temperature	200	°F
Final zone temperature	2192	°F
Approximate area of opening	5	ft^2
Production rate	60	tons/h
Speed	150	m/min
Density of steel	490	lb/ft^3
Length of the strip	118	ft
Width of the strip	4	ft
Thickness of the strip	0.0016	ft
Temperature of the strip at entry	70	°F
Preheat temperature	300	°F
Temperature of the strip at exit	860	°F
Thermal conductivity of the steel strip	26	Btu/hr.ft.F
Specific heat capacity of the steel sheet	0.115	Btu/lb-F
Input cfm of natural gas	130	m^3/hr
Input cfm of air	1400	m^3/hr
Density of air at ambient temperature	0.075	lb/ft^3
Specific heat capacity of air at ambient temperature	0.24026	Btu/lb-F
Stack temperature	1800	°F

*(Conversion factors: 1 MMBtu = 1.055 GJ; K = (459.67 + F)/1.8; 1 m = 3.2808 ft.; 1 ft. = 12 inches; 1 W/m-K = 0.5778 Btu/hr-ft-F; 1 kg = 2.2046 lbs; 1 J/kg-K = 0.0002 Btu/lb-F; 1 m^2 = 10.7639 ft^2; 1 ton = 907.1847 kg; 1 lb/ft^3 = 16.0185 kg/m^3).

Figure 3 Research approach



3.2 Preparing data collection sheet

The operating characteristics of the equipment found in the facilities were carefully studied. The major energy consumption points at various stages of the process were identified and a survey form was prepared so that all the energy-related information for the particular energy points could be gathered precisely. The survey form was designed in the form of tables to facilitate the data collection process. Table 6 shows an example data collection form for electric motors. Table 7 shows an example data collection form for natural gas equipment.

Table 6 Example of data collection sheet for electric motors

Equipment name containing the motor							
HP	*No. of motors of same HP*	*Load factor* (%)	*Utilisation factor* (%)	*Number of standby motors*	*Are the motors running during shutdowns* (*YES/NO*)	*Load factor during shutdown* (%)	*Eff.*
60	2	60	80	1	NO	60	91

Table 7 Example of survey form for different natural gas equipment

Equipment name	*MMBtu/Hr or SCFH for each burner*	*Number of burners with same capacity*	*Load factor* (%)	*Utilisation factor* (%)	*Recuperator* (*Yes/No*)	*Status during downtime* (*On/Pilot/ Low Fire*)	*Load factor during shutdown* (%)
Pre-heat section	0.24	24	80	100	Yes	ON	20

(Conversion factors: 1 MMBtu = 1.055 GJ).

The basic formula to calculate the input energy is,

$$\text{MMBtu/h} = \Sigma\{\text{HP} \times (N - n) \times \text{LF} \times \text{UF} \times \text{C/Eff}\} \tag{3.1}$$

where

HP: Horsepower of the motor

N: Total number of motors of same horsepower

n: Number of standby motors

LF: Load Factor

UF: Utilisation Factor

C: Conversion Factor HP to MMBtu/h (0.002547)

Eff: Efficiency

(1 MMBtu = 1.055 GJ)

The summation of MMBtu/h (1 MMBtu = 1.055 GJ) for all the motors entered by the user will provide the total energy consumed by the motors. Additional variables such as life span of the motor, efficiency and their load during shutdown period are also built in the model.

The input energy consumed by other electric equipment and the natural gas equipment can be calculated using similar approach. The energy consumed by the natural gas equipment is calculated as,

$$\text{MMBtu/h} = \Sigma\{M \times N \times \text{LF} \times \text{UF/Eff}\} \text{ (without recuperators)} \quad (3.2)$$

or

$$\text{MMBtu/h} = \Sigma\{(M \times r) \times N \times \text{LF} \times \text{UF/Eff}\} \text{ (with recuperators)} \quad (3.3)$$

where

M: Burner rating (MMBtu/h)

N: Number of burners of same capacity

LF: Load Factor

UF: Utilisation Factor

Eff: Efficiency

r: Reduction in gas consumption as a result of recuperators

(1 MMBtu = 1.055 GJ)

If the input for the gas burners is given in terms of SCFH, the above-mentioned formula is multiplied by a factor K (0.001) to convert the units to MMBtu/h (1 MMBtu = 1.055 GJ). The formula with input given in SCFH is shown in equations (3.4) and (3.5).

$$\text{MMBtu/h} = \Sigma\{S \times N \times \text{LF} \times \text{UF} \times \text{K/Eff}\} \text{ (without recuperators)} \quad (3.4)$$

or

$$\text{MMBtu/h} = \Sigma\{(S \times r) \times N \times \text{LF} \times \text{UF} \times \text{K/Eff}\} \text{ (with recuperators)} \quad (3.5)$$

where

S: Capacity of burner in SCFH

K: Conversion factor form SCFH to MMBtu/h (0.001)

(1 MMBtu = 1.055 GJ)

The survey form was developed as an aid to obtain the necessary information required for the model in addition to the data sheets, which act as input for the benchmarking calculations. These survey forms are part of the DSS and comprise the input section of the model.

3.3 Conducting measurements and field surveys

The survey forms were filled with the information obtained from the visits conducted at three different galvanising facilities. Some of the instruments used to conduct the measurements were electrical load monitoring equipment, stroboscope, infrared temperature gun, thermal camera and combustion gas stack analyser. In addition, onboard data available from computers controlling the galvanising line were also referred. The online controllers provided information like load factors on the electric grids for the zinc pots, natural gas consumption in different sections of the annealing furnace and the set point and current temperatures at different points in the process. The data measured as well as that obtained from the facility were used to refine the GEPDSS. The data collection fields were simplified and aimed to obtain the most accurate information. These visits resulted in promising information for analysis and further study.

3.4 Analysis of data and simulation for savings

The GEPDSS analyses the input data and provides results in term of energy required per unit production for different products, its cost and hardware economics. These results will reflect the current scenario in the concerned continuous galvanising line. The results depend on the production rate, production time and downtime. If any new pot hardware is used, its performance will impact the production and reduce downtime. This increase in production or number of turns can be obtained for the first few months of service for the new hardware. On the basis of the performance, the data can be extrapolated for the whole year. It will provide information about the energy consumption per unit production and other production details when the new hardware is used. Comparing these new results with the original results, one can evaluate the energy savings and other benefits resulting from the use of the new hardware.

3.5 Generation of results

The output expected from GEPDSS is established in the form of 'Summary sheet', which provides monthly details of total production, 'Energy consumption sheet', which provides the energy consumed by equipment for production as well as non-production periods, Production and Rejection details. Economic analysis is also performed for the pot hardware material. Graphs are presented to show the results.

3.6 Sensitivity analysis

The GEPDSS has a quick sensitivity analysis module to analyse the effect of the increased up time on production and energy consumption. The sensitivity analysis is based on constant production rate and production schedule. It has an average value for energy consumption per hour and calculates the current work schedule from the production data provided as an input. The user can input the new schedule and quickly compare the results for the new production and energy consumption. It is expected that using this analysis, the user can make a decision as to how long a particular product should be scheduled to minimise the energy consumption and allocate preventive maintenance shutdowns.

4 Model development

4.1 Developing the Excel™ – VB interface

The model is developed to handle up to three different processes performed on the same galvanising line. This resulted in development of four independent Excel™ files, each consisting of a number of Excel™ sheets. One file represents one particular process and each file consists of multiple spreadsheets called modules. These modules are interconnected with formulas and share data within the four Excel™ files. The handling of these four files was out of the scope of Visual Basic Application (VBA) in Excel™. Thus, an independent VB.NET programme was developed that was capable of handling and accessing these Excel™ sheets while working out of Excel™ environment. This makes it necessary for the model to be installed on a computer. The programme enables access to any specific spreadsheet of any one of the Excel™ files. The entered data is stored on the hard drive in these Excel™ files. Since files are dedicated to individual processes, once the data is entered for a particular process, it is stored in the memory unless altered by the user. The files are stored in a location on C drive specified during installation of the programme.

Figure 4 shows the architecture of the DSS. The boxes represent the four different files. The input and output modules are specified in the boxes. The arrows represent the flow of information from one file to the other. One or multiple modules may use the information. Each Excel™ file has a separate calculation module at the end of the file. This arrangement prevents damage to the modules by mistaken deletion of the data. All the input values are exported to the calculation module and only the results are shown in the output modules. Also, data sharing within the files is done from the calculation modules only.

Figure 4 Architecture of Decision-Support System

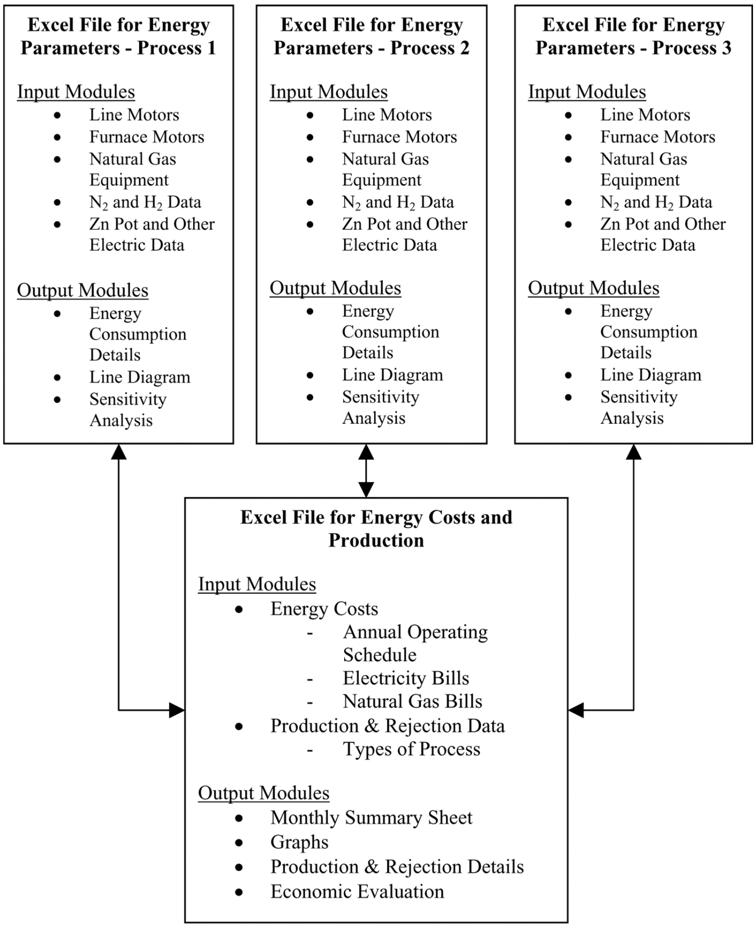
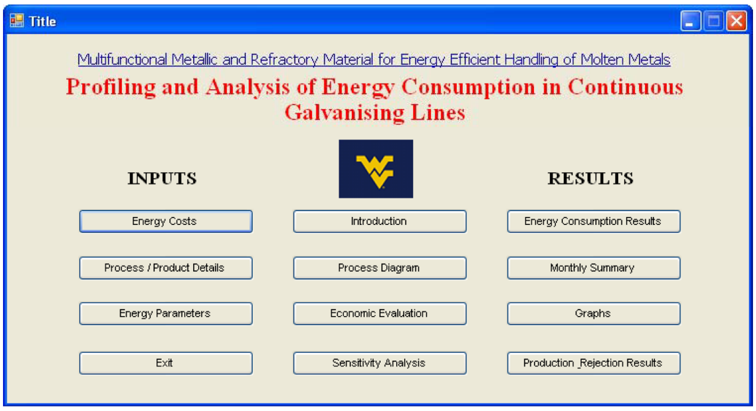


Figure 5 shows the VB form that user will see as soon as the programme is executed. This page helps the user to navigate through different sections of the model. On the basis of the user selection, a specific module of a particular file will be opened or further options will be provided to the user. This not only facilitates the handling of multiple files and modules, but also makes the model more rigid and stable. If the user chooses to fill in data relating to a process, a pop-up screen will prompt the selection of the process for which the data is to be entered or modified.

Figure 5 Title form (see online version for colours)



4.2 Inputs

The input sections links those modules where the user is required to fill in data pertaining to electricity and natural gas costs, details of processes, nitrogen and hydrogen consumption, production and equipment capacity and utilisation for each process selected. Various options are provided to the user to fill in input data.

4.3 Outputs

The output section provides the power and energy consumption details, nitrogen and hydrogen consumption details for each process, summary sheet with a comprehensive chart providing monthly data and a line diagram for entire line for all the processes.

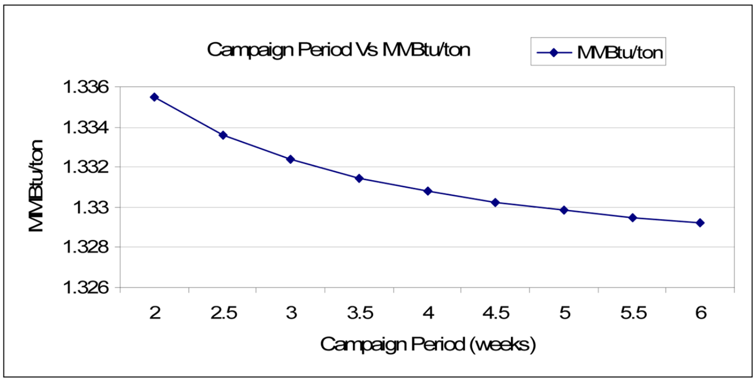
4.4 Sensitivity analysis

This tool helps the user to realise the benefits obtained as a result of increased production and energy savings. In this section, all the data pertaining to energy, production hours and downtimes is obtained or calculated from the input data. The current campaign period for the line is calculated and based on the average production rate and average downtime, the annual production is estimated. The consumption of energy to produce the calculated galvanised steel is also obtained.

The user can change the average downtime, which by default is the same as that for the current scenario. By applying these changes, the user will find the new value of production in tons (1 ton = 907.1847 kg) of galvanised steel and amount of energy required to produce this quantity. The dual benefits of increasing the campaign period can be expressed as increased annual production and the amount of energy saved. The energy savings per ton (1 ton = 907.1847 kg) can be calculated by comparing the new production volume and related energy consumption with the old production volume and related energy consumption.

Figure 6 is plotted with campaign period on the *X*-axis and the specific energy consumption in MMBtu/ton (1 MMBtu/ton = 1.1629×10^{-03} GJ/kg) on the *Y*-axis. It can be observed that the specific energy consumption drops down considerably in initial weeks. After five weeks of campaign period, the slope of the curve is reduced.

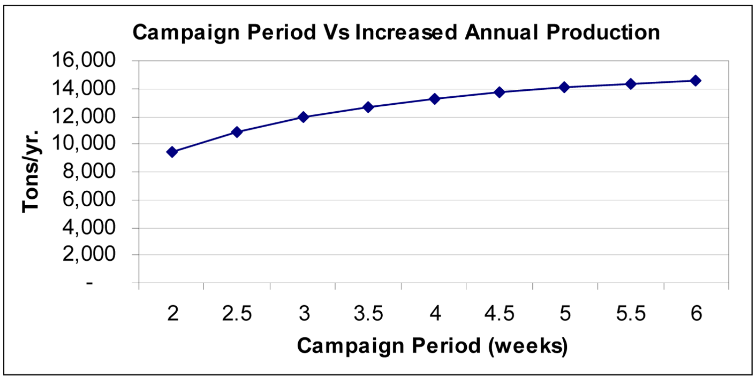
Figure 6 Graph of campaign period vs. MMBtu/ton (see online version for colours)



(1 MMBtu/ton = $1.1629*10^{-03}$ GJ/kg).

Figure 7 is plotted with campaign period on the *X*-axis and the increased annual production in tons (1 ton = 907.1847 kg) on the *Y*-axis. The increased annual production is the additional production obtained as a result of increased campaign period. It can be observed that the production increases from 8500 tons (1 ton = 907.1847 kg) in a two-week campaign to 14,000 tons (1 ton = 907.1847 kg) in a 5-week campaign. However**,** the increase in production after 5-week campaign is not significant. As seen from the graph, the production in the 6-week campaign is less than 15,000 tons (1 ton = 907.1847 kg).

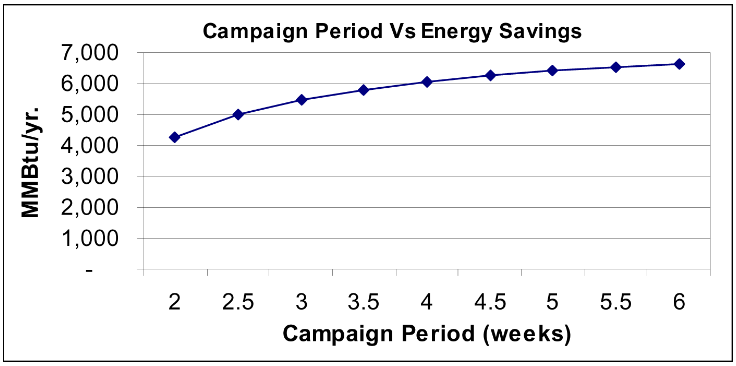
Figure 7 Graph of campaign period vs. increment in annual production (see online version for colours)



(1 ton = 907.1847 kg).

Figure 8 shows a plot of campaign period vs. energy savings obtained as a result of increased campaign period. It can be observed that the slope of the curve starts reducing after around 4.5 weeks of campaign period.

Figure 8 Graph of campaign period vs. energy savings (see online version for colours)



(1 MMBtu = 1.055 GJ).

It can be concluded that significant impact is produced on specific energy consumption (MMBtu/ton) (1 MMBtu/ton = 1.1629×10^{-03} GJ/kg). It is observed that there is considerable increase in annual production (tons/year) (1 ton = 907.1847 kg) and energy savings (MMBtu/year) (1 MMBtu = 1.055 GJ) with increase in campaign period up to five weeks. The impact on these parameters diminishes with further increase in campaign period. In addition, it has been noted that the equipment, other than the pot hardware, needs maintenance within four weeks of operating period. Most of the facilities have been observed to perform a planned maintenance shutdown every three weeks, since motors, pumps and other such equipment needed attention. Thus, even with an extended pot hardware life, the campaign period will be restricted to four-week duration with the existing technology.

4.5 Economic evaluation

If the investment for new pot hardware is considerably higher than the existing hardware, an economic evaluation can be performed to calculate return on investment (ROR). The analysis is performed for a 52-week period and the Modified Internal Rate of Return (MIRR) is calculated. The user can enter the desired rate of return to calculate the MIRR. The default value of the desired rate of return is 5%. The MIRR is calculated as follows:

$$\frac{\text{Future Value of Net Cash Inflow}}{\text{Present Value of Net Cash Outflow}}$$

$$= \frac{\sum_{n=0}^{N} \max(F_n, 0)(1+i)^{N-n}}{-\sum_{n=0}^{N} \min(F_n, 0)(1+i)^{-n}} = (1 + MIRR)^N \tag{4.1}$$

where

$\max(F_n, 0) = F_n$ if $F_n > 0$, otherwise $F_n = 0$

$\min(F_n, 0) = F_n$ if $F_n < 0$, otherwise $F_n = 0$

i = Minimum attractive rate of return for the firm (MARR).

If the MIRR is greater than the desired rate of return, the investment is justified.

5 Validating results and future work

5.1 Validation process

The validation of the GEPDSS was done using data from four different facilities, two of which were entirely new data sets. Even though the basic galvanising process is the same, the equipment present in every facility varies a lot. Accurate data pertaining to different equipment capacities, production and other parameters were obtained for the input section. The result from the summary sheet provides the annual kWh (1 kWh = 0.0036 GJ) for electricity and MMBtu (1 MMBtu = 1.055 GJ) for the natural gas calculated by the spreadsheet. This gave the total annual energy consumed by the facility. This value was compared with the total annual energy reported on the energy bills for the facility. A factor was considered to eliminate the energy consumed by plant lighting and HVAC from the energy bills for the facility. On the basis of the information received from galvanising facilities, it was found that approximately 10–12% of the annual energy is consumed by plant lighting, HVAC and other small office and lab equipment. A value of 12% is used in the calculations for validation. This amount is reduced during comparison since the model does not account for this energy consumption. The facilities will be identified as Facility 1, Facility 2, Facility 3 and Facility 4. This is done to protect the identity of the facilities as per the non-disclosure agreements. Table 8 shows the comparison between the calculated energy values and the energy values from the utility bills.

The table shows that the difference between actual and calculated energy consumption averages to 3.73%. The difference can be attributed to energy consumption in lighting, HVAC, etc.

Table 8 Comparison between actual and calculated energy consumption

	Annual energy consumption from energy bills (MMBtu/yr)	*After lighting and HVAC deduction 12%* (MMBtu/yr)	*Average annual energy calculated by the model* (MMBtu/yr)	*Percentage difference* (%)
Facility 1	972,588	855,877	823,005	3.84
Facility 2	639,288	562,573	550,931	2.07
Facility 3	524,537	461,593	439,306	4.82
Facility 4	593,063	521,895	500,024	4.19
Average				*3.73*

(Conversion factors: 1 MMBtu = 1.055 GJ).

5.2 Results from sensitivity analysis

Figure 9 shows the sensitivity report for Facility 3 with the increased campaign period scenario. The report is prepared for a 70-day campaign period and has calculated 48,833 tons (1 ton = 907.1847 kg) of annual increase in production and $193,549 energy cost savings. These values were discussed with the facility staff and were determined to be achievable and practically feasible.

Figure 9 Sensitivity analysis for increased campaign period

Calculations for 10.00 Week/s Campaign	70	Day Cycle
Average No. of weeks operated before shutdown	10	weeks
Production in given weeks	72240	tons
Furnace energy consumption for production weeks	85948.81483	MMBtu
Misc motor energy consumption for production weeks	13828.29362	MMBtu
Zn Pot energy consumption for production weeks	2803.19592	MMBtu
Operating weeks per year	51	weeks/year
Average Shutdown duration in hours	10.00	hours
Total operating hours	8,568	hours/year
The number of maintenance shutdowns per year	5	shutdowns/year
Total Production time	8,517	hours/year
Total down time (during shutoff)	51	hours/year
Energy consumed by plant during production	520,064	MMBtu/year
Energy consumed by plant during shutoff	1,024	MMBtu/year
Total Annual energy consumption	521,088	MMBtu/year
Total Annual Production	366,244	tons/year
Energy consumption per ton of steel produces	**1.42**	MMBtu/ton
Increased annual production	**48,833**	**tons**
Energy Savings per ton	**0.07**	**MMBtu/ton**
Total Energy Savings due to increased production	**26,616**	**MMBtu/yr**
Total Annual Energy Cost Savings	**$193,549**	**$/yr**

(1 MMBtu = 1.055 GJ).

5.3 Summary sheet results

The monthly summary for one of the facilities is attached in Figure 10.

Figure 10 Extract from summary sheet (see online version for colours)

Month		MMBtu/ton
January		
	GL - Stru Steel	1.49
	GL - Soft Steel	1.26
	GL - Non-Annea	
February		
	GL - Stru Steel	
	GL - Soft Steel	1.27
	GL - Non-Annea	1.13

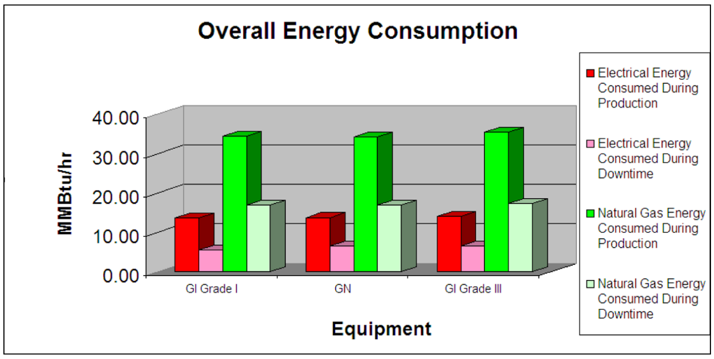
(1 MMBtu = 1.055 GJ).

5.4 Graphs

The graphs obtained for one of the facilities are shown in Figures 11–13.

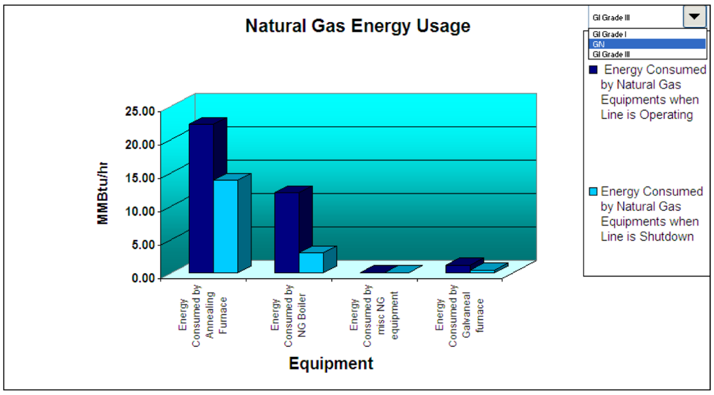
Figure 11 shows the energy consumed by all the electrical and natural gas equipment in MMBtu/hr (1 MMBtu = 1.055 GJ) during production as well as during downtime.

Figure 11 Overall energy consumption (see online version for colours)



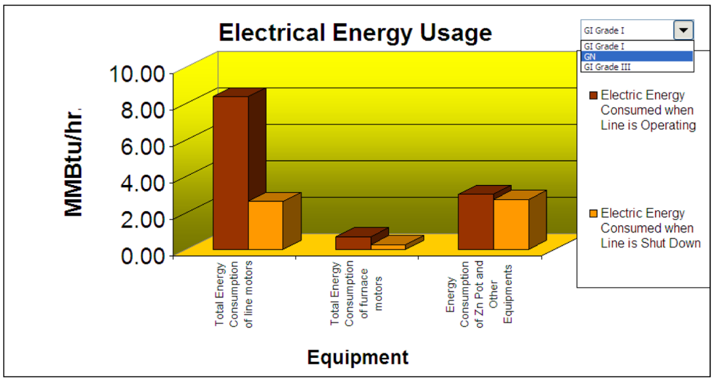
(1 MMBtu = 1.055 GJ).

Figure 12 Natural gas energy consumption (see online version for colours)



(1 MMBtu = 1.055 GJ).

Figure 13 Electrical energy consumption (see online version for colours)



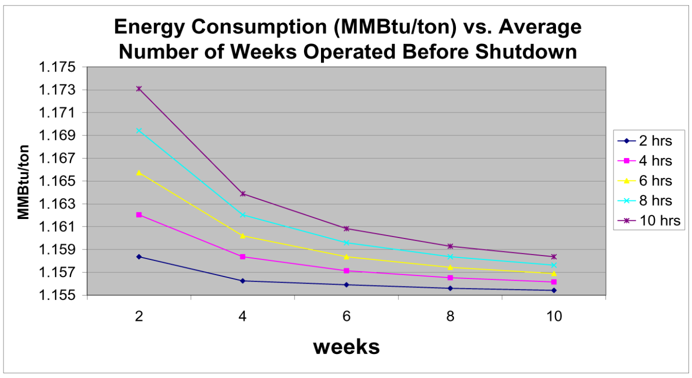
(1 MMBtu = 1.055 GJ).

Figure 12 shows the energy consumed by natural gas equipment, during production and downtime, for a particular process. The graphs have drop down menu to select the process for which the user wishes to see the energy consumption.

Figure 13 shows the energy consumed by electrical equipment during production and downtime for a particular process.

The variation of energy intensity (MMBtu/ton) (1 MMBtu/ton = 1.1629 $\times 10^{-03}$ GJ/kg) for a typical line that runs varying campaign periods (*X*-axis) prior to shutdown is shown (Figure 14) with respect to the time spent to get the line operating again after the shutdown. It is evident that as the campaign period increases owing to improved pot hardware, the time between line shutdowns does not play a major role in contributing to the variance in energy intensity. Lower campaign periods owing to poor pot hardware life or other reasons place a strong emphasis on reduction in time between shutdowns to reduce the energy intensity. Time between line shutdowns influences the economic desirability of purchasing and installing new pot hardware, as shown in Figure 15. For low campaign periods and high values for time between shutdowns, the expected MIRR will not be met in terms of investment desirability in new pot hardware. The energy impact of the model, if used by galvanising lines nationwide, is shown in Figure 16. It has been estimated that there are 60–70 galvanising lines in the USA. It has been assumed that each line has an average production capacity of 500,000 tons per year, with total natural gas and electricity costs close to \$5 million annually. The degree of penetration has been assumed to be immediate with respect to galvanising lines nationwide, as the implementation of the technology is not a complex task. Furthermore, the materials needed to improve the quality of the pot hardware have been commercially developed. Each line was assumed to currently operate with an average campaign period of 2.67 weeks with time for shutdown between campaigns to be 12 h. Under these conditions, the GEPDSS was executed to determine the energy savings that would result for the 70 galvanising lines if the campaign periods were increased and the time between campaigns were reduced. The GEPDSS calculates the energy and cost savings for one line and multiplies it by the number of lines. The *X*-axis in Figure 16 shows each 'instance' for all 70 galvanising lines for specific values of the campaign period and time between shutdowns. For example, instance '3' shows that for all 70 galvanising lines, when the campaign period was four weeks and time between shutdowns was 6 h, as opposed to the average values, the total energy savings would be close to 0.35 trillion Btu per year and the total cost savings would be \$ 3.25 million per year. The longer the campaign periods and the lower the time between shutdowns, the more the impact of energy and cost savings on a national level for galvanising lines, as shown in Figure 16.

Figure 14 Profile of energy consumption vs. weeks of operation (see online version for colours)



(1 MMBtu = 1.055 GJ).

Figure 15 Profile of MIRR vs. weeks of operation (see online version for colours)

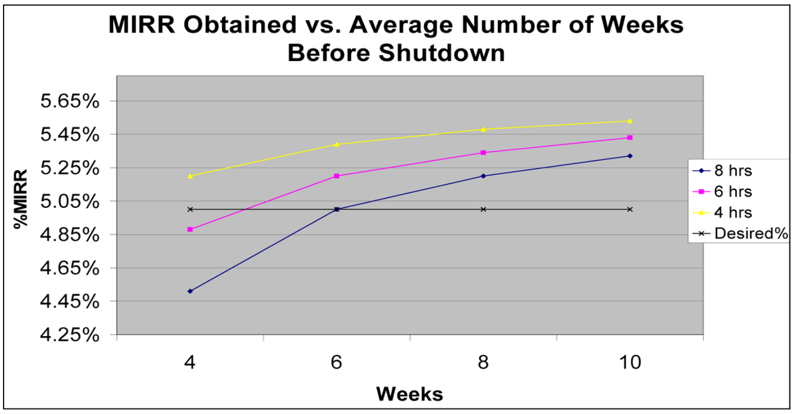
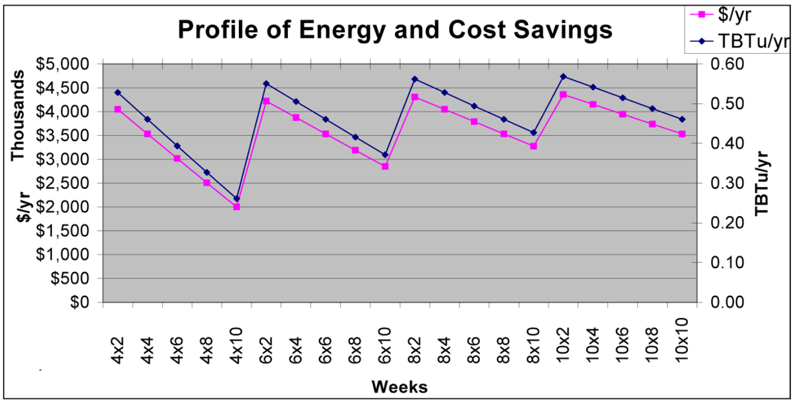


Figure 16 Estimated energy and dollar savings for galvanising lines nationwide (see online version for colours)



(1 TBtu = 1.055×10^6 GJ).

6 Conclusion

The length of the campaign period to produce a product type as well as the time between shutdowns of the line when changing from one product to another influences the energy intensity considerably. Improvement in pot hardware life coupled with improved maintenance practices that reduces the time between shutdowns is the key to energy savings and increased productivity. The model will assist in decision making with respect to investment in new pot hardware that will extend campaign periods. The model will provide the engineers a good comparison between product types with respect to energy and cost consumption and energy intensity. Changes made to the line in terms of motors, furnace equipment and pot characteristics can be evaluated in terms of energy, cost and productivity.

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