Benchmarking Production System, Process Energy, and Facility Energy Performance Using a Systems Approach

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ABSTRACT

Evaluating overall energy performance of a manufacturing system requires accurate information on how, when, and where energy is being used. Collecting and tracking energy data is necessary for determining performance benchmarks and reducing energy consumption. Optimizing energy efficiency in manufacturing systems is difficult to achieve since energy management is typically performed separately from the production monitoring and control systems. Further, low-level equipment energy data collection is costly to do, and, if done, is often not well-linked to production data.

The smarter integration of production system, process energy, and facility energy data is a significant opportunity to improve manufacturing sustainability. This paper will examine the issues related to the linking of these three types of data as well as develop a methodology for jointly modeling and evaluating production, process energy, and facility energy performance. A case study of a sand casting production line will be discussed to better understand the integration issues, validate the methodology, test performance benchmarks, and investigate sustainable manufacturing opportunities.

Categories and Subject Descriptors

J.1 [**Computer Applications**]: [manufacturing]

General Terms

Management, Measurement, Performance, Standardization

Keywords

Sustainability, Discrete Event Simulation, production, energy, methodology, analysis, key performance indicators (KPI)

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1. INTRODUCTION

The goal for manufacturing to be cleaner, more efficient, and environmentally benign is part of the dynamics contributing to a closer examination of manufacturing sustainability. Further, costs related to carbon emissions seen in the form of a potential "Cap and Trade" or a "Carbon Tax" scheme are considered by some to be inevitable. To stay competitive, companies must assess and improve their energy use within production in order to reduce their carbon footprint. Organizing, quantifying, and reporting of cumulative energy consumption and greenhouse gas emissions of manufacturing processes can be found in International Organization for Standardization (ISO) standards 14064-1, -2, and -3 [9, 10, 11] and ISO 14065-2006 [12], but thus far, there has been limited analysis of more automated, synergistic approaches to combined production and energy management.

More intelligent integration of process and energy data offers a significant opportunity to reduce manufacturing energy consumption [1, 2]. Energy management is challenging for manufacturing due to the difficulty that arises from the diversity of energy use – there are thousands of processes each having unique energy consumption characteristics as well as different production requirements based on the product, product quality, environmental compliance, and other business factors [16]. Today, most production energy management is done by separate plant information systems and is frequently not well-linked to production data. Though possible, it is quite costly, especially in older facilities, to perform extensive energy data collection at the equipment level. Consequently, low-level energy consumption within production is also not well understood. Clearly, without insight into the fundamental energy consumption behavior of equipment, it becomes challenging for plant and manufacturing engineers to make effective decisions. Further, facility energy such as heating, ventilation, and air-conditioning (HVAC) and lighting, which is viewed from an indirect perspective, is also loosely correlated to production needs. The smarter integration of production system, process energy, and facility energy management is a significant opportunity to improve manufacturing sustainability. If a smarter, more holistic, view of the manufacturing system were in place, simple actions such as the timely shut off an air handler when a production line is down could lead to energy reductions.

General Motors (GM) and the National Institute of Stan-

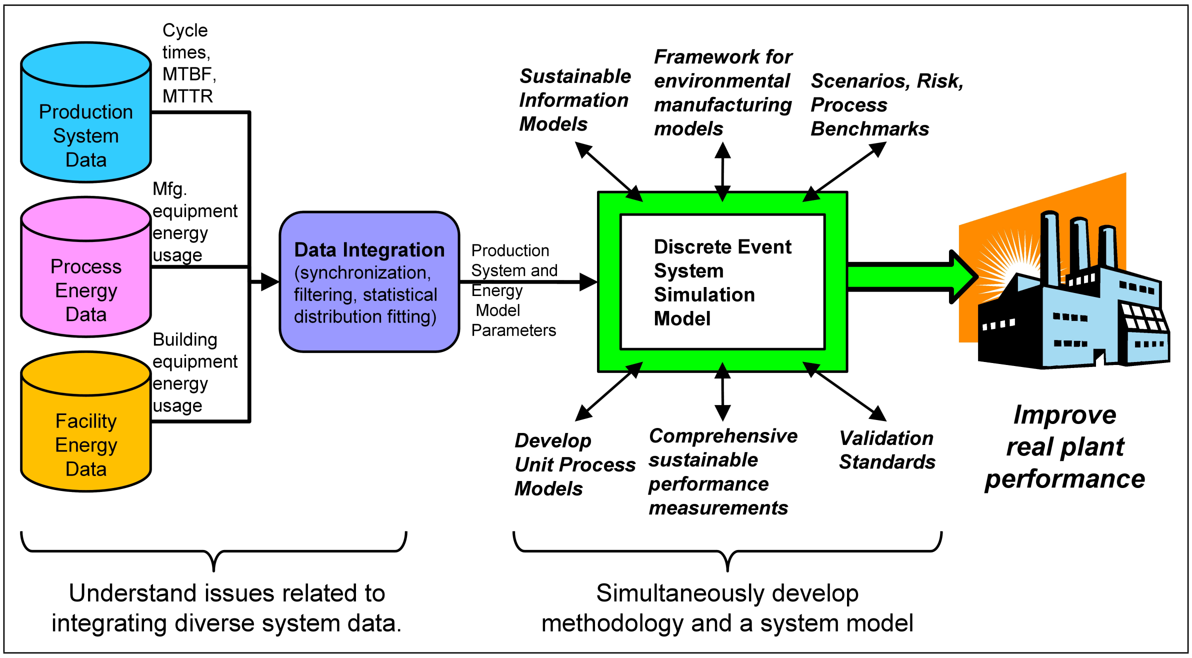

Figure 1: Integration of Production System, Process Energy, and Facility Energy Data for Sustainable Manufacturing

dards and Technology (NIST) are partners in an effort to investigate the feasibility of smarter integration of production, process energy, and facility energy data from the plant floor to improve sustainability. The goal of this effort is to understand the key technical and implementation issues in combining such data. The strategy adopted in this work focuses on developing a methodology to extract process and energy data from the plant, and then formalize this approach to allow future reuse at other production facilities. The formalism to measure and benchmark sustainability performance is considered a critical aspect as currently this production/process energy/facility energy integration is not done in a systematic fashion.

Fundamental to a smarter understanding of a process is the ability to measure it. Currently, prescribed energy reduction methods in industry are often related to lean manufacturing concepts and include energy treasure hunts, value stream mapping, Six Sigma, and Kaizen events [6]. Most of these methods rely on empirical observation and basic analysis. However, informative, accurate and timely shop-floor production data should be considered vital to understanding a process. Only with accurate data from the shop-floor can analysis and benchmarking be suitably done to eliminate waste and inefficiencies.

The research into energy efficiency of manufacturing processes covers the spectrum of industrial processes [7]. The majority of the research is on energy-intensive processes, where the energy gains would be most pronounced. Most of the research conducts a static analysis of a manufacturing process and then compares and contrasts various processing options and areas for potential improvement. Generally, energy efficiency research does not include consideration for automating the data collection and analysis in order to perform continuous monitoring of factory floor energy consumption.

Solding considered design issues related to energy and power utilization inside an iron foundry [15]. Heilala proposed an integrated factory simulation tool for the design phase to help maximize production efficiency and balance environmental constraints and present methods for calculating energy efficiency, carbon dioxide (CO_2) emissions and other environmental impacts [8]. This research considers energy consumption, but only estimates energy consumption based on equipment power ratings. Kuhl shows sustainability modeling and simulation of logistics and transportation systems, but does not incorporate real-time data collection [14]. Research into industrial process and energy analysis using Discrete Event Simulation (DES) has been shown to be possible, but illustrates the difficulty in incorporating real energy data into the DES process analysis.

Though many companies cannot afford sophisticated factory data collection, the low cost of networks and computers is continually lowering the financial threshold of acquiring plant information systems that can perform real-time data collection and archiving of the operational behavior of their HVAC, PLCs, automation, and other auxiliary equipment. Increasingly, companies collect process and energy data from the various control and supervisory systems on the plant floor and store the data in several different databases. Although process and energy data collection is routinely done, there are often many (and unconnected) data collection subsystems involved. Given such systems and databases, this work seeks to build an integrated production system and process energy and facility energy DES benchmarking model.

This paper will study the issues related to integration of production system and process energy and facility energy data as well as to develop a methodology for modeling and evaluating performance. Section 2 will discuss the concepts involved in the systems approach to the integration of energy and process for sustainable production. Section 3 will present a walk-through of the methodology as applied to production and process energy integration for a sand casting production line at General Motors. The methodology will include goals, objectives and assumptions; functional requirements; data collection; and modeling and analysis. Finally, section 4 will present a discussion on the results and future directions.

2. PRODUCTION SYSTEM, PROCESS ENERGY, AND FACILITY ENERGY INTEGRATION

Figure 1 highlights the concepts involved in the systems approach to integration of energy and production system data for sustainable manufacturing. Production system event, process energy, and facility energy data are all required to be collected from the factory floor and stored into archival databases. At this point, it is assumed that facility energy and production system data is not synchronized and stored in different databases. Process energy on the other hand such as the electricity used to power a computer numerical control (CNC) milling machine could be linked with event data. However, this data is frequently not readily available nor integrated unless a specific effort has been made to acquire the data from the machine controller or via power monitoring sensors. Data integration would thus involve a number of steps: data collection, cleaning and filtering, state and event correlation, and finally data fitting to statistical distributions. Given the production and energy (for both process and facility) data and statistical characterization, the factory is modeled in DES so that potential scenarios can be run to project different operational outcomes. The development of the DES model is a large undertaking but can be handled in phases to incorporate increasingly detailed parameterization, at first, starting with the basic key performance indicators (KPI) such as, cycle time, throughput, and bottlenecks, and then adding energy KPI: cost and energy consumption and CO_2 emissions.

For the determination of productivity, the use of DES is considered critical to developing a production and energy benchmarking methodology. In manufacturing, DES simulates a real or virtual model of production based on statistical characterization of a manufacturing process, such as cycle time, idle time, and failure rates. Once developed, the DES model can then be used to predict outcome given different parameterization scenarios. DES can also be used in the design of new facilities using historical production data to ensure modeling accuracy.

Assuming a robust model, DES is aptly suited as a way to understand energy consumption as it relates to process and facility control, as a DES model can run benchmark data to uncover optimizations, savings and drawbacks, as well as mitigate risks, and help avoid potential crisis points. For example, benchmarks could be used to understand the implications of energy usage during production stoppages, to understand the effect of changing production schedules, or to see what can be done to lower the risk associated with rising energy costs or energy shortages. Development of the DES model provides an apt framework in which to develop an integrated process and energy strategy. However, a one-time DES model is a necessary but not sufficient goal for this effort. Part of the mission is to generalize any modeling

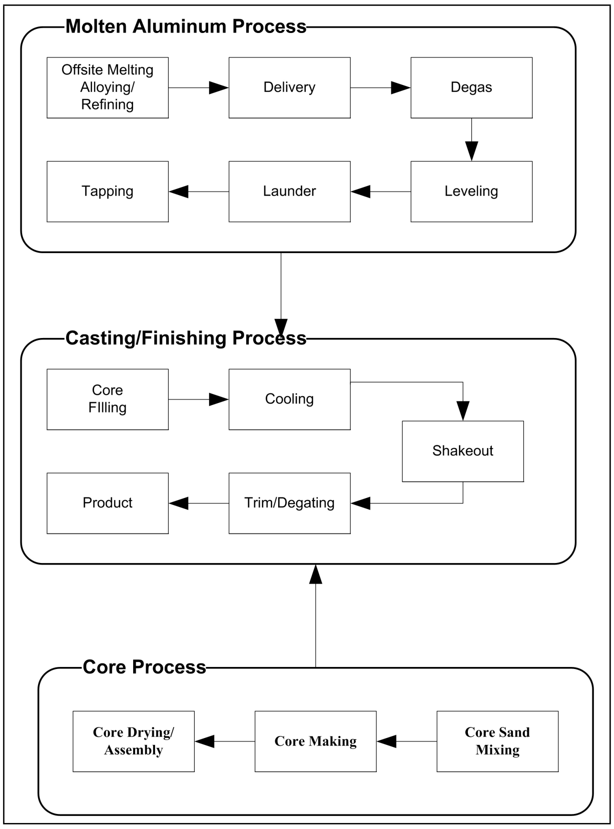

Figure 2: Casting Process

and analysis work to become part of standard sustainable technology. A goal of the work is to leverage the integrated production and process and energy modeling and develop a methodology that will allow such work in the future to be done in a systematic and formal manner. Understanding the issues related to integrating the diverse process and facility energy with production system data is a core part of the effort. The effort will contribute to the ongoing evolution in improving and standardizing sustainable manufacturing constituent technologies, including integrated frameworks based on composable components, information models, and performance metrics.

Figure 1 shows related technologies that assist and simplify sustainable manufacturing efforts, including unit processes, sustainable information models, sustainable frameworks, and performance metrics. Unit processes are defined as the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product [5]. Unit processes within manufacturing can involve one or more mechanical, thermal, electrical, or chemical processes. Improving the quality of the final product depends on improvements to the unit processes themselves. Sustainable information models use formal representations to model the full range of the product lifecycle and sustainable manufacturing, including reuse, recycle (disassembly), and remanufacturing. A framework for environmental manufacturing models allows composing sustainable manufacturing systems based on sustainable manufacturing components [13].

Given the goals of this work, numerous GM plants and

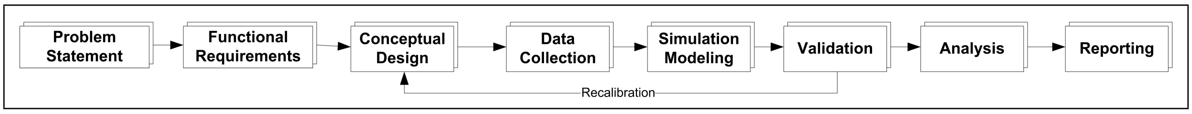

Figure 3: Energy and Process Model Methodology Steps

processes were investigated as a suitable candidate for a specific production and process energy and facility energy sustainable manufacturing study, in the end an aluminum casting production line was selected as it combined several key factors: significant energy consumption, extensive production system process and facility energy data collection, and the opportunity to benchmark the effectiveness of new technologies.

Casting has seen over 5000 years of technological advances. Figure 2 shows a high-level overview of the casting process at GM that is dedicated to making aluminum engine blocks. The molten aluminum process is responsible for melting the aluminum, refining the melt, and adjusting the molten chemistry. Once molten, the aluminum is degassed, leveled, and laundered to remove deleterious gases before being tapped to flow into cores. Cores are made of sand which is poured into molding machines to create the contours of the casting, pressed and heated to bind the sand. Since the sand casting process is an expendable mold metal casting process, the core process builds a new sand core for each casting. Overall, core parts are molded from sand and binding elements, assembled into the engine block core, and then dried before casting. The casting and finishing process is where the molten aluminum flows into the sand cast core, after which, the casting is cooled and then casting sand is removed from around the now solidified aluminum engine block by shakeout, trim, and degating operations.

3. METHODOLOGY

The goal of this GM/NIST effort is to develop a methodology that combines low-level production data and energy data in order to derive sustainable manufacturing benchmarks and cost projections. Ideally, the methodology should be generic and applicable to any process and facility.

A large number of modeling factors are critical in effectively developing a production and energy methodology for a manufacturing system. Manufacturing systems involve a number of interrelated elements, including equipment strategy, number of product options, material handling systems, system size, process flow configuration, processing time of the operations, system and workstation capacity, and space utilization. The model must be combined with other constraints such as unpredictable machine breakdowns, varying operational requirements, schedule variation, and different production demands.

Figure 3 shows the general foundation of the methodology that will be refined in the course of developing the production system and process energy and facility energy model. The application of these general methodology steps, as applied to the GM sand casting process, will be discussed in the following sections.

3.1 Problem Statement and Objectives

First, a problem statement with goals, objectives, assumptions, and simplifications must be developed. The problem is to model the relationship between process energy and facility energy within a production environment. The objectives are to better understand these relationship to improve energy efficiency, process efficiency, part quality, yield rate, and other established production objectives. The assumptions that facility energy and process data is available will be assumed, but the data may be poorly correlated or the energy data may not be of sufficient granularity to establish meaningful measures. Some simplifying assumptions will be made if the energy data does not satisfy the analysis needs, such that a future data collection plan will be developed that would enable the proper data collection to allow the energy and process control to be properly modeled. Another simplification is that high-level process KPIs will be sufficient for understanding process flow, and can be derived directly from the existing plant-floor information systems in place. The existence of data is high-fidelity will be assumed.

3.2 Functional Requirements

In this step, a list is made of the functional requirements that need to be satisfied for the model to be accurate. This step is also used to determine the appropriate scope and level of detail of the effort. For the functional requirements, the goal is to understand the key performance and sustainability indicators for the production and process energy consumption. Some of the related tasks involved in developing the detailed requirements include the following.

- Define the high-level methodology for efficient DES modeling of energy and process production.
- Develop reusable unit process model templates for casting and other production systems.
- Enumerate scenarios for the production and process energy study.
- Describe the tasks to correlate facility energy management with process energy and production system data.
- Structure the data collection and integration of energy data and process data.
- Identify potential energy optimizations and related decision tradeoffs.

3.3 Conceptual Design

Next, a conceptual design is required that provides a system model of the manufacturing system. The system model gives a high level description of the inputs and outputs for the parts, equipment, and general process flow, including energy requirements. At this point, only a rough estimate of the timing and interconnections of all the elements is required. The basic information required by the conceptual design analysis includes:

1. process flow,
2. production statistics,

3. resources – equipment list,

4. and energy resources

Resource energy consumption can be modeled quite effectively using a state model, which maps machine energy usage to particular states [4]. Equipment such as fans, machinery, or lighting all can be modeled by finite state machines. Figure 4 shows the basic state model for machinery resources in our project, where the equipment has states for off, busy, idle, down, starved, and blocked states. Such a model is particularly useful because it is equally applicable to equipment whether they be for production or for the facility. The only difference is that for facility equipment, the starved or blocked states would never arise.

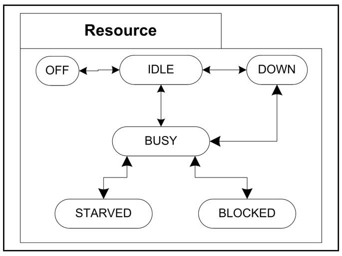

Figure 4: Production Equipment State Model

The Off state indicates that the process equipment is not in use (unpowered). The Busy state indicates the equipment is working to produce product. The Starved state indicates that there are missing input materials so the equipment is paused. If the storage facility for the process output is full, the process is in the Blocked state and the equipment is paused. When equipment has a breakdown or fault, the process stops and the equipment is in the Down state.

Some equipment need not have such a complex state model and instead may only exhibit the Off or Busy or Down states. For example, a light has on/off states, but can also be down (i.e., broken). Understanding the necessary state model for each piece of equipment is important so that correct data can be properly collected. For example, knowing the amount of total energy that is consumed during the entire day may not be sufficient. Rather, knowing the average amount of energy consumption within each state is more important in developing a robust model.

Detailed information contained in the system model of the production line should include:

- number of resources – including state model,
- number and size of buffers,
- type of parts,
- estimated energy required to make parts,
- general high level overview of material in parts,
- transport between resources, conveyor speeds,
- and overview part routes between resources.

3.4 Data Collection

Data collection involves the activities required for obtaining accurate and meaningful representations of all the relevant input parameters for the system model. Specific data interfaces and acquisition logic is required to collect both static and dynamic data. Static data defines constant values, such as buffer sizes, and can be fed into the conceptual design. Dynamic data refers to process and energy state that can change over time.

In our study, production system and process energy data are routinely archived to databases. Normal data handling operations, such as filtering of the raw data into event data as well as cleansing of the data, are required, as in any modeling work. Production data can be described by raw, cumulative eventŮbased, or statistical distribution parameters.

Raw data obtained via regular polling contains a timestamp, the current state and any other knowledge deemed important. If the energy data is uncorrelated to process data, the most useful form of energy data would be as archived raw data with timestamp and energy intensity values, (e.g., kW). Table 1 shows an example for raw data entry the production system.

Table 1: Raw process data

Line	Object	State	Timestamp
PSC	Machine1	Idle	02/22/2010 06:19:00
PSC	Machine1	Busy	02/22/2010 06:20:00
PSC	Machine1	Busy	02/22/2010 06:21:00

Raw polled data can become voluminous without some filtering or aggregation into cumulative data. The casting plant data collection filtered raw data into event data containing events and time duration within the event. Table 2 shows an example of event–based data that describes production.

Table 2: Filtered Event Process Data

Line	Object	Event	Start Time	End Time
PSC	Machine1	Idle	02/22/2010 06:19:00	02/22/2010 06:19:06
PSC	Machine1	Busy	02/22/2010 06:19:08	02/22/2010 06:22:44
PSC	Machine1	Blocked	02/22/2010 06:22:46	02/22/2010 06:23:04

Assuming the data has been collected, database queries can then retrieve the relevant process and energy data to characterize the factory operation. Production can then be succinctly characterized by fitting event data to a statistical distribution. Throughput, utilization, and cycle time are some KPIs that often statistically characterize manufacturing performance.

Table 3 shows a statistical characterizations of cycle time and down time that is required for DES to model production. The data must be in the form of production system data, such as cycle time per part, not as cumulative time equipment spends in each state, that is, total time spent in the busy versus idle state during the course of a shift. This is due to the need to understand the relationships of cycle time to part yield as well as to incorporate equipment failure and its influence on the overall system model.

Table 3: Statistical Process Data

Line	Object	Average Cycle Time	MTBF	MTTR	
PSC	Machine1	67.7	38.0	42.0	
PSC	Machine2	70.0	27.7	15.2	
PSC	Machine3	72.2	23.5	36.5	

On the other hand, process energy data is based on integrated measurements over time to determine power consumption, but may include peaks, spikes, and other cost-sensitive parameters. For this analysis, the key energy parameter is not only power consumed, but now, instead of time-based readings, the energy needs to be correlated to the underlying process state, for example, the amount of energy being consumed while processing, versus the amount of energy being consumed when the equipment is down. However, synchronizing the energy data to the process within the plant is difficult as energy collection is integrated over time, and energy collection is uncorrelated to process performance. This means that energy data needs to be transformed from timed into state-based power consumption. If the energy data is of fine enough granularity, the transformation can be programmatically determined by correlating the power consumed during a process state and integrating over time. Should the energy data be coarse readings, such as daily or shift summaries, numerical algorithms will be required to perform statistical and selective modeling techniques that can roughly estimate the power consumed for the process states.

In general, the following is a representative but not exhaustive list of data that should be collected:

- resource and production data and statistics,
- process cycle times,
- process setup times,
- resource mean time between failure (MTBF),
- resource mean time to repair (MTTR),
- process scrap percentage (if any),
- resource/process energy consumption,
- and resource conveyor speeds.

3.5 Simulation Modeling

Building the DES model links the system model with the data collection activity. It assumes that statistical fitting of the data collected yields acceptable results. The DES model will then assist in the manufacturing decision-making process. The major consideration during this phase is the level of detail to model. To attain more insightful energy related decisions, a finer granularity of modeling is necessary. If possible, the energy consumed by each piece of equipment should be incorporated into the DES model. If the data collection phase is able to determine state-based equipment energy consumption, then it can be easily calculated during DES analysis scenarios.

3.6 Validation

A validated model is both accurate and able to meet the high-level functional requirements of the problem statement. The purpose of validation is to guarantee that the behavior of the model is representative for the system modeled. Numerous validation tests can be done, but the comparison with the real casting production system as a means of establishing whether the system model is accurate will be used. Of course, further mathematical analysis can be used to augment and confirm the accuracy of the initial validation. If the DES system outputs do not compare well with the actual system outputs, then further analysis for missing items in the system model, or closer attention to the data collected to verify its accuracy will need to be done. This process is repeated until the model is satisfactory either through empirical observation or by statistical analysis [3].

3.7 Analysis/Results

When the model has been validated and is ready for use then various scenarios can be created to evaluate production system, process energy, and facility energy performance. DES can then benchmark the overall manufacturing system to evaluate concepts, identify problem areas, and quantify or optimize system performance.

First, DES can benchmark process performance. Often, improving process performance will correspond to energy savings, but not always. If the production line is often down, and the production equipment use less power while idling, then less energy will be used. So, some production improvements such as better yield may end up using more energy, but are a positive. Clearly, reducing scrap corresponds to energy savings. This implies that production really needs to study the energy cost per part yield to truly understand the performance benchmarking of energy consumption. Potential process scenario criteria include:

- throughput and bottleneck identification,
- utilization of resources, labor, and machines,
- staffing requirements, capacity, and work shifts,
- storage needs, and queuing at work locations,
- routing of materials,
- and maintenance and down time.

Typical industrial energy consumption analysis relies heavily on empirical observation. This has proven useful but most of the easily sustainable savings have been realized. Using integrated production system and process energy data, new potential savings will have to be identified based on automated and more scientific scenarios and assessment. First, with an automated approach the data is more reliable than with empirically observed phenomenon, but may be harder to understand. Second, real data will help detect subtle problems that are not readily apparent. For example, process and energy variability can be monitored with real data, and significant variability may imply underlying production problems.

The foreseen scenario analysis includes:

- Correlate total energy consumption to parts produced per shift to develop a production energy yield.

- Determine average and peak loads for given energy yield. Assess variability.

- Compare energy yield against an equipment energy baseline determined from rated power to compute equipment energy sizing factor.

- Compare daily variability of process energy consumption. Determine root cause in cases of high variability.

- Compare energy consumption pre/post preventive maintenance. This scenario can assess operation when equipment and processes are expected to run efficiently.

- Compare energy consumption between high and low scrap rate.

- Compare yield to energy to outdoor temperature.

- Adjust electrical cost to determine change in per unit cost.

- Change fault times to determine change in electrical consumption.

- Assess amount of equipment energy consumed versus rated power of equipment. Excessive powered equipment should be replaced with smaller equipment tailored to the specific needs of manufacturing cells.

- Maximize electricity purchasing power, evaluate opportunities to reduce energy costs through load shifting of electricity use to off-peak times, assuming energy deregulation is applicable.

- Determine if real-time power shedding to reduce the load and limit the peak load cost is required, compare to production efficiency, where high production efficiency correlated to minimal or no corresponding downtime, blocked or starved subprocesses, assuming the capability for power metering to predict the electrical demand.

4. DISCUSSION

In this paper, a methodology for analyzing the smarter integration of production system, process energy, and facility energy data was outlined. In this section some preliminary results and related modeling issues from our analysis of the selected GM casting production system and process energy integration will be presented. Note that this initial work does not yet include the facility energy data, however, the specific details and issues with the integration of this data is ongoing at the time this paper was written and will be left for a future report.

Some initial observations are in order. This particular GM sand casting production is a large process, with hundreds of electrical equipment being controlled – robots, conveyors, elevators, sand core making machines, saws, etc. The extent of the casting production size necessitated narrowing the initial analysis scope to one of the finishing lines. The analysis was also limited to data already being collected by the plant's production system.

DES modeling to integrate production system and process energy data requires that traditional production KPIs be combined with process energy KPIs. Raw and event process production data was available and easily adapted into process KPI parameters. The casting production facility has a target castings yield per hour that it must achieve. This target served as the baseline process performance benchmark. Access to baseline energy equipment data for rated and peak energy loads was also available for most of the plant equipment. Logically, the production system data and the process energy data were not an exact match within production line, with production data being grouped a little differently than that of the energy data. For this analysis, the modeling was restructured to satisfy the structure of the energy information.

Using a commercial DES software package, a model was developed to correlate the production activity with the process energy consumption. This was not straightforward as the DES package did not inherently support manufacturing sustainability concepts, but correlation of the data by separating the integration into production and process energy submodels was possible. The Finishing process was condensed into three steps to better match the energy data: Spiral Cooling, Blast Robot, and Degating. Cycle times were determined by summing constituent process data substep cycle times. In simulation, the casting is moved from process to process. The operations (Spiral Cooling, Blast Robot, and Degating) have equipment resources that were simulated with the Sieze–Delay process model [17]. Once the simulated delay is completed, the casting is moved forward in the simulation lines. Input and output queues are associated with each operation, but queue states (blocked/starved), conveyor times, buffering, were not addressed in this initial analysis.

A state-based model to calculate energy consumption was used, where the resource utilization is used to determine the amount of energy consumed. For the initial benchmarking analysis, the rated equipment electrical demand loads as estimates for determining the "Busy" and "Idle" power consumption was used. Energy consumed was calculated using the native DES performance statistics for resource utilization, which provides values in the range from zero to one, and the total time of the simulation. The total resource energy consumed in the "Busy" state is determined by multiplying the resource utilization by the simulation time and by the average power used in this state. "Idle" is calculated similarly but uses 1 minus the utilization. Down time was not factored into the current stated based energy calculation. As an example, we can determine the total energy consumed for the blast robot during the simulation by the following equation:

$$\begin{aligned} E_{BR}^{Total} &= ((SU(BRR, Busy) == 1) \\ &\quad \times E_{BR^{Busy}} \\ &\quad +1.0 - (SU(BRR, Busy) \\ &\quad \times E_{BR^{Idle}}) \times T_s \end{aligned}$$

where

$BR = Blast\ Robot\ Process\ Module$
$BRR = Blast\ Robot\ Resource$
$E_x = Energy\ for\ Resource\ at\ State\ x$
$SU(resource, state) = utilization:\ u \in [0,1]$
$T_s = Total\ Simulation\ Time$

The total energy is the sum of each process energy consumption and the total energy cost is based on industry estimate of 5 cents per kWh price.

In summary, this paper has presented an approach to develop system models which can be used to evaluate the overall energy performance of any given manufacturing system. The total energy consumed in a manufacturing plant is comprised of process and facility energy components. Process energy is directly related to the operation of production lines that must meet specified targets. Facility energy consumption though not directly linked to production system performance nevertheless can be indirectly attributed and correlated with the requirements of the manufacturing system. The distinction between these two types of energy data though seemingly obvious is not trivial. Facility energy data typically resides in plant energy management systems that monitor and control the operation of equipment such as HVAC and other building related automation. Process energy on the other hand is not so readily available and often requires additional programming and interfacing effort with machine controllers to extract it and subsequently store it in some plant-floor system database. Many times, such process energy data is viewed in isolation from both the production system and certainly from that of the facility energy management system. The separation of these two types of energy data clearly represents an integration challenge, however, if successfully done, the association and correlation of this data can tremendously enhance the capability of a plant to make better energy related decisions. Therefore, any attempt to obtain meaningful understanding of a plant's total energy consumption thus requires a modeling approach that encompasses the interactions of the production system with that of the energy consumption characteristics of its equipment whether they be process or facility related.

In addition, process and facility energy analysis requires systematic study of strategic points within production lines. Production facilities can be very complex that makes integrated energy assessments quite difficult. Using a systematic methodology with appropriate benchmarks and evaluation criteria can make this a more manageable activity. However, energy results and the relationships to production are not always intuitive. For example, a paradox of lean manufacturing principles applied to energy consumption is that process improvements may in fact lead to increased energy consumption, but will improve part energy yield. Given an environment where energy efficiency improvements and technologies are not as easy to come by, production system, process energy, and facility energy data integration and benchmark measures are even more important to determine the expected return-on-investment of any energy-related improvements.

Disclaimer

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