Network Modelling with Digital Twins for Energy Efficient Industrial Systems

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Abstract – The energy efficiency framework in this paper accounts for the dynamic interdependencies between production equipment and facility's technical services. By annotating activities with nodes and flow (of materials and/or energy) between them by arcs, a complex network is constructed. Material flow includes parts, subassemblies, waste materials, etc. Depending on the granularity of the analysis, these nodes can be simple or composite with a sub-network beneath them. Nodes across a network are interdependent in terms of "Energy Consumption" in such way that energy reduction in one node may lead to increase/decrease in energy consumption of upstream/downstream nodes. Consequently, the total energy reduction due to a mitigation action taken at a node is the sum of *Direct* and *Indirect* effects. We will show how these effects can be quantified. By the same token, nodes have "Performance" interdependencies; therefore, energy reduction in one node might improve or degrade the performance in another node (measured in some KPIs). Hence, the balance between energy efficiency and performance (which quantifies both productivity and waste) must be accounted for in any energy optimization strategy.

Introduction

Typical industrial plants and complexes include machines and workstations for industrial processes and office space for business and other related technical functions and services. The existing practical and academic works for energy efficiency of these systems usually fall into one of the two generic categories, "Industrial Facility" and "Industrial Process". At "Industrial Facility", the focus has been on reducing the energy consumed by facility's infrastructure and technical services (e.g. lighting, heating and cooling), see, for example, Moynihan and Barringer [2017] and Andreassi et al. [2009]. For "Industrial Process", the focus has been on reducing energy consumption in industrial equipment, machinery and workstations. Common models use scheduling/planning and physics-based methods to achieve reduction in energy consumption of industrial processes. For instance, Fang et al. [2011] and Chen et al. [2013] developed operational models to minimize energy usage of equipment in manufacturing systems through effective scheduling of machine start-up and shutdowns. Dietmair et al. [2008] and Bi et al. [2012] provide guidelines for energy efficiency by analysing mechanical components in industrial processes.

In this article, we argue that independent analysis of energy usage patterns in "Industrial Facility" and "Industrial Process" fail to cover all aspects and potentials for energy reduction. The paper highlights the need for a more integrated view of energy efficiency in industrial complexes. We argue that the dynamic interdependencies between production equipment and facility's technical services must be holistically included in energy efficiency analysis and optimization. Energy optimization has to be performed over all activities that contribute to making of a product (See Salahi et al, [2013]) or to delivering of a service. By annotating activities with nodes and the flow (of materials and/or energy) between them by arcs, a complex network emerges. Depending on the granularity of the analysis, these nodes can be simple or composite with a sub-network beneath them. In many instances these nodes are owned by a single entity or business unit. It is also possible for the network to includes interdependent entities or business units that contribute to making of a set of products or managing industrial processes. For instance, a typical waste management complex may consist of several interdependent units that contribute to processing and deposing wastes.

Nodes across a network are interdependent in terms of "Energy Consumption" in such way that energy reduction in one node might increase/decrease energy consumption in another upstream/downstream node. Consequently, the total energy reduction at a node is the sum of *Direct* and *Indirect* measures; *Direct* energy reduction is the result of applying energy saving solution in the node itself whereas *Indirect* reduction is the impact of implementing a saving solution to other nodes of the network. By the same token, nodes have "Performance" interdependencies; therefore, energy reduction in one node might actually improve or degrade the performance in another node, as measured in terms of appropriate Key Performance Indicators (KPI). Whilst a number of research works have incorporated such an integrated view to investigate the energy consumption within an industrial environment, they come far short of providing an algorithmic and systematic approach to measure the interdependencies between components (See Rahimifard et al. [2010] and York and Relf [2019]).

Here we intend to formalize industrial energy efficiency as a network optimization problem that help achieve energy efficiency by determining the amount of energy reduction plausible for each node of the network. We present an innovative framework to model and effectively capture the dynamic interdependencies between components of an industrial system, in terms of "Energy Consumption" and "Performance". The paper makes contributions both in its integrative approach and in taking into account interdependencies between processes and services. The conceptual framework and optimization model are generic, but calculation details are application dependent. Therefore, we will use an illustrative example for demonstration purposes. The network optimization problem is formulated next, under general assumptions. Using a production system as an illustrative case, "Performance" and "Energy Consumption" interdependencies are identified and quantified. Given a set of feasible energy saving solutions for the illustrative case, the network optimization is analysed and solved.

Nomenclatures

x_j = Direct energy reduction in node j stemmed from energy saving solution S_j' (kWh), $x_j \geq 0$
PER_j= Maximum 'Potential Energy Reduction' in node j (kWh), $PER_j \geq 0$
PRF_j= Current Performance at node j (before energy reduction solution) in terms of appropriate KPI
v_j= Economic value generated per unit energy reduction at node j ($/kWh)
c_j = Cost of each unit energy reduction at node j ($/kWh)
ESR= Total 'Energy Saving' requirement at network (kWh) (Constant)
B= Total economic budget for energy reduction at network ($) (Constant)
β_j = Economic budget for energy saving solution at node j($) (Constant)
p_j= Penalty per unit energy increase at node j ($/kWh) (Constant)
r_j= Economic reward per unit performance improvement at node j (Constant)
l_j = Penalty per unit performance degradation at node j (Constant)
δ_{ij}= "Energy" Dependency: Energy reduction/increase in node i per unit energy reduction in node j, ($\delta_{ij} \epsilon R$)
ρ_{ij}= "Performance" Dependency: Performance improvement/degradation in node i per unit energy reduction in node j, ($\rho_{ij} \epsilon R$)
E_j = Energy consumption of node j in base scenario (kWh)
PM_j= Performance of node j in base scenario (relevant KPI)
E_j' = Energy consumption of node j when energy saving solution is implemented (kWh)
PM_j' = Performance of node j when energy saving solution is implemented (relevant KPI)

Preliminaries

We consider a generic industrial plant, which includes one or more production processes (e.g. production lines) and a facility (e.g., a building) that houses these processes as depicted in Figure 1. A network of interdependent nodes emerge mapping energy consuming activities into nodes and their material or energy dependencies into arcs connecting these nodes. We assume that owner(s) of the above system is (are) determined to reduce the overall energy usage of the system by a certain quantity. It is also assumed that there are economic incentives for improving energy efficiency in each node, which means energy reduction at each node results in a reward for owners. Moreover, nodes have specific "Performance" requirements defined in terms of appropriate KPIs; thus, any deviation from such requirement is penalized.

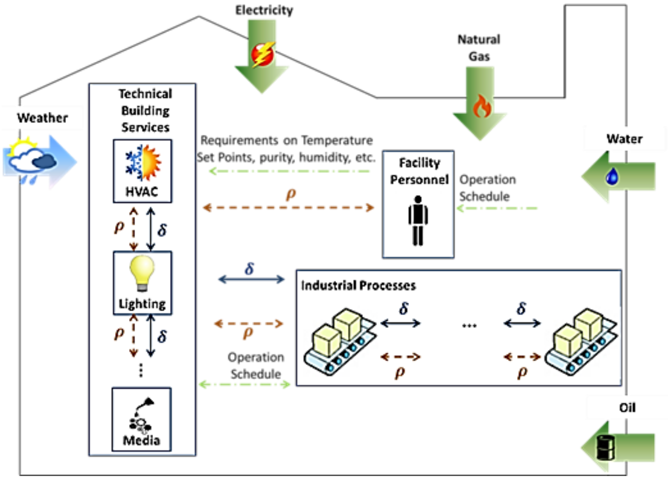

Figure 1- An Industrial System as a Network of Interdependent Nodes

As depicted in Figure 1, our network is comprised of two composite groups of nodes: (1) Industrial Processes (2) Technical Services in the facility's building. One major task for technical services is to ensure that temperature, humidity and moisture and other environmental conditions are properly maintained through heating, cooling and air conditioning. We focus on HVAC (Heating, Ventilation and Air Conditioning) to provide these conditions. Besides, technical services are responsible for providing essential media such as compressed air, steam and cooling water for industrial processes. In this paper for illustrative purposes, we assume that the industrial process is a serial production line consisting of three workstations or work centers. The components of HVAC system studied here are (1) electric variable speed chiller, (2) hot water boiler and (3) electric supply fan.

Problem Statement and Network Formulation

The problem of interest is to determine the energy reduction share of each node (x_j, $j \in \Omega$) in the network. The network includes all the energy consuming units (facility or process levels). Note that x_j is the Direct energy reduction at node j stemmed from energy saving solution imposed on j (S_j). As noted earlier, nodes across the network are interdependent in terms of "Energy Consumption" and "Performance". "Energy" dependency between nodes i and j (first order dependency) is denoted by δ_{ij}, where, positive 'Energy' dependency ($\delta_{ij} > 0$) is defined as the amount of energy reduction in node i per unit energy saving in node j. Negative 'Energy' dependency, ($\delta_{ij} < 0$), is the increase in node i's energy consumption, as a result of energy reduction in node j. Similar definitions hold for positive and negative 'Performance' dependency hereafter denoted by ρ_{ij}. For simplicity, it is assumed that (a) one energy saving solution is applied at a time on each node j, (b) only first order "Energy" and "Performance" dependencies are accounted for, that is, the impact of simultaneous energy saving solutions on multiple nodes is assumed to be negligible.

Network Optimization

We assume that the following input data are available: (1) economic reward and penalty data; (2) nodes' minimum "Performance" requirements (η_j); (3) maximum potential energy saving technically and economically viable for each node (PER_j); (4) Economic budget at node and network levels. Due to economic incentives for energy use reduction, the energy efficiency optimization problem can be considered as a profit maximization problem; hence, the objective function, is the sum of the profits obtained through Direct and Indirect energy reduction at each node which is stated as:

$$\mathrm{Max}\ \{\sum_{j=1}^{n}(v_j c_j)x_j + \sum_{j=1}^{n}\left(\sum_{i\neq j=1}^{n}(v_i - p_i)\,\delta_{ij} + \sum_{i\neq j=1}^{n}(r_i l_i)\,\rho_{ij}\right) x_j\,\} \tag{1}$$

where the first and second terms are profit functions through Direct and Indirect energy reduction respectively.

Constraints:

Minimum energy saving requirement (ESR) need to be achieved at network level by applying Direct and Indirect energy reduction at individual nodes.

$$\sum_{j=1}^{n} x_j + \sum_{j=1}^{n}\sum_{i\neq j=1}^{n}\delta_{ij}x_j \geq \mathrm{ESR} \tag{2}$$

Reduction in a node's energy usage is subject to technological, physical and economical limitations; therefore, energy saving at a given node cannot exceed the pre-defined maximum potential energy reduction at that node. Moreover, each node's share of energy saving is non-negative.

$$x_i + \sum_{j\neq i=1}^{n}\delta_{ij}x_j \leq \mathrm{PER}_i \quad \forall i = 1, \dots, n \tag{3}$$

The owner has limited monetary budgets for energy reduction at network level; moreover, penalties due to performance degradation as well as energy increase at any node, are deducted from nodes predefined budgets.

$$\sum_{j=1}^{n} c_j x_j + \sum_{j=1}^{n}\left(\left|\sum_{i\neq j=1}^{n} I(\delta)_i p_i \delta_{ij}\right|\right)x_j + \sum_{j=1}^{n}\left(\left|\sum_{i=1}^{n} I(\rho)_i l_i \rho_{ij}\right|\right)x_j \leq B \tag{4}$$

$$c_i x_i + I(\delta)_i p_i\left(\left|\sum_{j\neq i=1}^{n}\delta_{ij}x_j\right|\right) + I(\rho)_i l_i\left(\left|\sum_{j\neq i=1}^{n}\rho_{ij}x_j\right|\right) \leq \beta_i \quad \forall i = 1, \dots, n \tag{5}$$

where,

$$I(\delta)_i = \begin{cases} 0 \text{ if } \delta_{ij} \geq 0 \\ 1 \text{ if } \delta_{ij} < 0 \end{cases} \quad \forall j = 1, \dots, n$$

$$I(\rho)_i = \begin{cases} 0 \text{ if } \rho_{ij} \geq 0 \\ 1 \text{ if } \rho_{ij} < 0 \end{cases} \quad \forall j = 1, \dots, n$$

All the nodes across the network are subject to minimum required performance characterization. That is, their performance in terms of appropriate KPI should not degrade below a required threshold as a result of Direct or Indirect energy saving.

$$\sum_{j=1}^{n}\rho_{ij}x_j + \mathrm{PRF}_i \geq \eta_i \quad \forall i = 1, \dots, n \tag{6}$$

Equation (6) underlines a very important relationship between energy and performance. It emphasizes the fact that in real applications, energy reduction strategies can be acceptable only to the extent that they do not disrupt performance requirements. To expand on this idea, we introduce what we call *"Energy-Performance*" curves, which show the direct relationship between energy use and an important KPI of an industrial system (e.g., system throughput rate measured in number of units, number of production batches, or production volume). In practice, "Energy-Performance" curves are quantifiable from historical data, simulations and/or process monitoring. Clearly "Energy-Performance" curve for a given industrial system depends on system control, input and output requirements, and system degradation and, henceforth, on maintenance policies and routines which are practiced within the system.

Nodes Interdependency Characterization

Energy optimization is contingent on the type of energy saving solutions available at each node. Different energy reduction solutions on nodes lead to distinctive results in terms of nodes energy and consumptions interdependencies.

Furthermore, there might be differences in the amount of reduction achieved on a given node through various solutions. In this work a set of common alternatives are chosen for energy saving at nodes in an industrial system for which interdependencies and optimization results are presented.

Energy Saving Solution Alternatives at Node

For technical services, we incorporate a setback control strategy at the HVAC system in which energy saving is achieved by avoiding unnecessary high temperatures and excessive cooling during heating and cooling seasons, respectively. In base case scenario, HVAC components are assumed to have fixed and continuous daily schedule in which chiller and boiler are operational all day during cooling and heating seasons, respectively. Energy reduction with setback control is achieved via shutting down chiller and boiler in off-peak daily shifts. For industrial processes, different energy reduction solutions can be adopted, including proactive maintenance policies, replacement of old equipment with more advanced machinery, advanced control solutions, etc. Here we will only focus on advanced control solutions that manipulate process variables (e.g., process speed) to regulate the industrial process. More specifically we incorporate a control solution (Linear Control) to reduce the waste of energy due to sudden shifts between operation modes. This will be discussed in more detail later.

Energy Usage and Performance Calculations at Nodes

To carry out the energy optimization, metered or summary data on energy usage and performance characteristics of the nodes are required. We define three metering approaches, namely, physical, virtual and simulated: In physical metering approach, KPIs and energy data are directly obtained from sensors or smart meters; Historical data along with inferential statistical techniques using facility utility bills, accounting databases, and equipment specification and performance data may be used to derive the virtual metered data; In the absence of meters and historical data, simulation may be used to obtain the required information on energy consumption and node performance. In this paper, we present general formulation, which can be supported by one or all of the above data metering approaches. For demonstration purposes we use simulated metering approach to derive necessary energy consumption and performance data.

Energy Calculation for an isolated Workstation

For industrial processes, we start from a single isolated workstation (WS) , where E_{WS} is the energy used by the station over a production shift with duration of T given as follows:

$$E_{WS} = \int_{t=0}^{T} P_{WS}(t)dt \qquad (7)$$

$P_{WS}(t)$ is the power input to WS at time t. E_{WS} is calculated according to station's operational states and the duration of time it spends in each state. A given workstation may experience different states, e.g., busy, idle, under repair or waiting for repair, etc. With regard to the processing power demand (P_{WS}), a variable and fixed portion can generally be differentiated (Dahmus and Gutowski, [2004]). The fixed power covers the constant demand, which is necessary to ensure a functional mode of operation (the idle state associated with low power rating). The process-induced portion relates to the power consumption that is used to do the actual work. The relationship between this power and the speed by which the work is done needs to be understood. For some application, the relationship between energy consumption and processing rate or speed has been experimentally calculated and verified in many instances. We differentiate between functional and operation modes, the former one is when the station is working on an actual job, whereas in the latter one the station is on but not necessarily doing any actual work. Energy consumption profile of various equipment were summarized by Diaz et al. [2011]; these profiles effectively highlight the relationship between energy consumption and performance (i.e. "Energy-Performance" curve). Generally speaking, as the EPR increases the processing time is reduced. Therefore, the contribution of the constant power demand of the station to the energy per unit processed decreases. However, an increase in EPR may increase the power demand, but may be with slow slope. Rate of effective processing can be considered as an appropriate KPI for monitoring performance of an equipment. In general, choosing appropriate process parameters is essential to balance performance vs energy usage.

Digital Twin for Energy usage calculation

Here, we describe the methodology to develop the underlying logic for digital twin of a tandem system and the formulation to compute its energy consumption. The digital twin can be implemented using MATLAB or any off-the-shelf simulation platform. The total energy usage depends on the number of workstations, energy and performance profile of each station, and non-value added times (such as starvation, blockage or any waiting times). The non-value added quantities are dependent on the configuration of the system, its input and output and control solutions put on stations and the whole system.

Let us consider a tandem system with three workstations and buffers for work-in -process (WIP) in between as depicted in Figure 2. Workstation $\mathrm{WS_i}, i = 1,2,3,$ is starved if buffer $\mathrm{b_i}$ (upstream of the workstation) is empty and it is blocked if $\mathrm{b_{i+1}}$ (downstream of the workstation) is full. Stations stay in "Idle" state during starvation and blockage states. A production cycle is defined per job processed in the system. At the beginning and end of an n-cycle episode the stations go through "Warm-up" and "Shut-down" states.

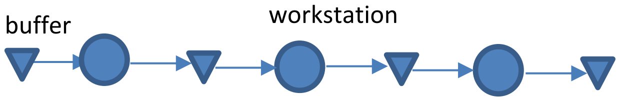

Figure 2 - Tandem System Configuration

We define the following state variables based on typical workstation operational states:

$$\mathrm{S_i} = \begin{cases} 0 & \text{if } \mathrm{WS_i} \text{ is down} \\ 1 & \text{if } WS \text{ is warming up} \\ 2 & \text{if } \mathrm{WS_i} \text{ is at run} - \text{time} \\ 3 & \text{if } \mathrm{WS_i} \text{ is idle} \\ 4 & \text{if WS is processing} - \text{working on a job} \\ 5 & \text{if WS is shutting down} \end{cases}$$

Consider the following random variables:

$\underline{\omega} = (\omega_1; \omega_2; \ldots; \omega_j \ldots)$; ω_j is random duration of a production cycle
$\underline{\varphi} = (\varphi_1; \varphi_2; \ldots; \varphi_j \ldots)$; φ_j is random duration of a visit to state 0
$\underline{\psi} = (\psi_1; \psi_2; \ldots; \psi_j \ldots)$; ψ_j is random duration of a visit to state 1
$\underline{\zeta} = (\zeta_1; \zeta_2; \ldots; \zeta_j \ldots)$; ζ_j is random duration of a visit to state 2
$\underline{\chi} = (\chi_1; \chi_2; \ldots; \chi_j \ldots)$; χ_j is random duration of a visit to state 3
$\underline{\theta} = (\theta_1; \theta_2; \ldots; \theta_j \ldots)$; θ_j is random duration of a visit to state 4
$\underline{\beta} = (\beta_1; \beta_2; \ldots; \beta_j \ldots)$; β_j is random duration of a visit to state 5

Thus, a single production cycle can be described by:

$$\omega_j \cong \{\varphi_j, \psi_j, \zeta_j, \chi_j, \theta_j, \beta_j\} \qquad (8)$$

Thus, for an n-cycle episode production, we have:

$$\omega_j{}^k \cong \{\varphi_j{}^k, \psi_j{}^k, \zeta_j{}^k, \chi_j{}^k, \theta_j{}^k, \beta_j{}^k | 1 \le k \le n\} \qquad (9)$$

Energy consumption for each of the above states of the workstation is a random variable, since the durations and processing rates (if applicable) are random variables. Suppose function $\pi : S \rightarrow$

Energy consumption. In practice, π () is a measurable function using any of the metering techniques that we discussed earlier. Here we will use simulation and to that end we develop a digital twin model for our illustrative case study. The digital twin keeps track of the random variables described above and tracks production cycles. It usually runs for multiple episodes and for a given episode one can estimate the following function using sampled simulated data. For episode j, the energy consumption estimate given by:

$$E_{WS_i} = \left[\pi\left(E(\varphi_j)\right)\right] + \left[\pi\left(E(\psi_j)\right)\right] + \left[\left(\pi E(\chi_j)\right)\right] + \left[\pi\left(E(\zeta_j)\right)\right] + \left[\pi\left(E(\theta_j)\right)\right] + \left[\pi\left(E(\beta_j)\right)\right] \quad (10)$$

Production cycles and duration of visits to aforementioned states depend on the control solution in place to regulate the workstations. These control schemes are embedded into our digital twin of the industrial process. Two rule-based control solutions are used, namely "High-Low" and "Linear" control in which a workstation's process rate is regulated on the basis of upstream and downstream buffer levels. In "High-Low" control workstation process (or effective work rate) rate fluctuates between two values (EPR_L and EPR_H). Figure 3, shows profile for "Processing" state of a single production cycle under the "High-Low" control. Multi-stage production cycles are characterized by a sequence of multiple single cycles separated by idle, runtime and warm-up times. The duration of time spent processing at EPR_L and EPR_H (i.e. τ_L and τ_H respectively) are usually measurable. The fluctuation between process rates are controlled based on the upstream and downstream buffer levels according to the following algorithm:

If b_i is near empty ($b_i \leq \alpha b_{max_i}$) or b_{i+1} is near its maximum capacity ($b_{i+1} \geq \alpha' b_{max_{i+1}}$),
WS_i works with EPR_L.

If $b_{i+1} \leq \alpha b_{max_{i+1}}$ or $b_i \geq \alpha' b_{max_i}$ WS_i works with EPR_H (11)

If b_i and b_{i+1} are in their "safe range" ($\alpha b_{max_i} \leq b_i \leq \alpha' b_{max_i}$ and $\alpha b_{max_{i+1}} \leq b_{i+1} \leq \alpha' b_{max_{i+1}}$)[1] the possibility of starvation (for downstream) or blockage (for upstream) is low, therefore WS_i continues processing with no change in the EPR.

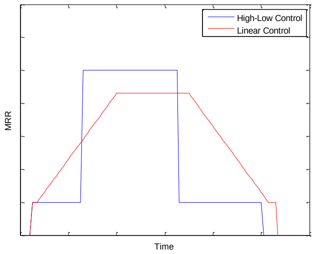

Figure 3-Single Production Cycle-"High-Low" vs. "Linear" Control

Energy usage rate of Low Control mode is considerably lower than High Control mode. Furthermore, changing from Low mode to High mode requires an acceleration step which consumes energy at considerable high rate. Using Linear control technique, workstation's process rate is regulated in such way to smooth out the impact of acceleration due to shift from "Low" to "High" mode. The process rate of WS_i can change linearly with different slopes. According to this rule-based control, whenever b_i is near empty ($b_i \leq \alpha b_{max_i}$) or b_{i+1} is near its maximum capacity ($b_{i+1} \geq \alpha' b_{max_{i+1}}$), WS_i's process rate is decreased with a s slope (units/second). Deceleration in process rate continues until buffers enter the safe range ($\alpha b_{max_i} \leq b_i \leq \alpha' b_{max_i}$ and $\alpha b_{max_{i+1}} \leq b_{i+1} \leq \alpha' b_{max_{i+1}}$). If $b_{i+1} \leq \alpha b_{max_{i+1}}$ or $b_i \geq \alpha' b_{max_i}$, process rate is increased with a s' slope and acceleration continues until buffer units reach safe range. Once the

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[1] Note that α & $\alpha' > 0$ are constants measured in percentage of buffers' maximum capacity.

buffers are at safe range, WS_i's process rate is kept constant, since the possibility of starvation or blockage is low. Notice however that switching from "High-Low" to a "Linear" control has a drawback of stretching the process time as is shown in Figure 3. Such phenomenon highlights the necessity of considering the "Energy-Performance" curve while making decisions on adopting the control policy to achieve energy reduction. In other words, process time increase is accepted so long the throughput stays above the demand requirement. Later in this paper, this concept is further elaborated for an illustrative case.

Heating, Ventilation and Cooling (HVAC) System

Energy consumption and performance data for HVAC equipment is derived using EnergyPlus digital twin. Figure 4 shows an example digital twin built using EnergyPlus.

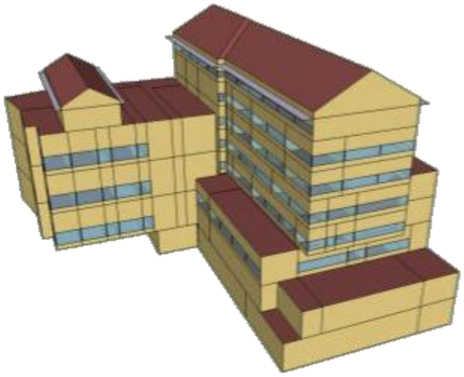

Figure 4 – Building digital Twin

EnergyPlus, developed by Department of Energy is an energy analysis thermal load simulation software that models heating, cooling, lighting, ventilation and other energy flows of a buildings and communities. Given user inputs for building physical description and associated mechanical systems, EnergyPlus calculates heating and cooling loads necessary to maintain thermal control set points, as well as HVAC equipment performance KPI and energy consumption in a deterministic manner. Note that temperature fluctuation in the facility as a result of imposing energy saving solutions, impacts the productivity of facility personnel. Such impacts can be accounted for using temperature outputs from EnergyPlus simulation runs and quantitative relationships between thermal comfort and occupant task performance as addressed in literature (e.g., Fanger, [1972]; Kosonen at al, [2004] and Lan, et al, [2011]). 'Performance' dependency between the facility's personnel and HVAC equipment is derived using 'Productivity', which is a measurable KPI in occupant performance evaluation studies. Task related performance of workers in a facility is significantly correlated with the human perception of thermal environment that in turn depends on temperatures (see Kosonen at al., 2004). The definition of occupant's 'Thermal Comfort' and Fanger's 'Predicted Mean Vote' (PMV) is used here to derive a quantitative relationship between personnel 'Productivity' and thermal environment. For a detailed discussion on methods to quantify a relationship between occupant's productivity and temperature fluctuations, see (Salahi et al, [2013b]). We use the polynomial function introduced by (Kosonen at al, [2004]:

$$\mathrm{RP} = 1.6\mathrm{PMV}^5 - 1.55\mathrm{PMV}^4 - 10.4\mathrm{PMV}^3 + 19.23\mathrm{PMV}^2 + 13.4\mathrm{PMV} + 1.87 \quad (12)$$

Energy & Performance Dependency Parameters

Energy usage and performance data are used to derive interdependencies between nodes (δ_{ij} and ρ_{ij}). Changes in node i's energy usage and performance upon energy saving in other nodes are derived as follows: (a) nodes' energy usage (E_i) and performance in terms of appropriate KPIs (PM_i) are metered and recorded when no energy saving solution is in place; (b) Energy saving solutions introduced earlier, are implemented one at a time and nodes' energy usage and KPI are measured (E_i' and PM_i'); (c) Energy dependency is defined as:

$$\delta_{ij} = \frac{E_i - E_i'}{E_j - E_j'} \qquad (13)$$

Nodes i and j are said to have positive energy dependency, denoted by $\delta_{ij} > 0$, if node i's energy consumption declines as a result of energy saving in node j. In other words the value $\delta_{ij} > 0$ represents energy reduction in node i due to 1 kWh energy saving in node j; (d) Performance dependency is defined as:

$$\rho_{ij} = \frac{PM_i - PM_i'}{E_j - E_j'} \qquad (14)$$

Positive 'Performance' dependency between nodes i and j is denoted by $\rho_{ij} > 0$. Such relationship holds when 'Performance' of node i, in terms of appropriate KPI, is improved as a result of energy saving in node j. It is worth to mention that while performing the nodes' interdependency calculations, energy saving solution is imposed on nodes one at a time.

Experimental Results

For our case study we use a validated digital twin of a building from DoE's publicly available model archives. The building simulation is executed using "USA_OL_Chicago-Ohare.Intl.AP.725300_TMY3" weather file. The operation schedule for HVAC components is changed from a continuous to a schedule with equipment shutdowns in off-peak hours. Appropriate HVAC equipment's efficiency measures (i.e. chiller cooling efficiency (EIR-fPLR), boiler heating efficiency (HIR-fPLR) and fan's specific power (SFP)) are used as appropriate KPIs to obtain "Performance" interdependencies. The digital twin includes several correlation curves that predict the energy use of HVAC systems under part load conditions. These correlation curves are intended to predict efficiency as a function of the part load ratio. In this paper, we use default curves given by the EnergyPlus simulation package and coefficients provided by (Henderson, Huang and Parker, [1999]).

A subset of machine specific power requirement data from empirical studies are used (Diaz et al., [2011]) for our analysis. As noted earlier, dynamic performance interdependencies between nodes, need to be considered while making decision on imposing energy reduction solutions so as to ensure demand requirements are successfully satisfied. Figure 5 shows the "Energy-Performance" curve for the example tandem industrial process, comparing "High-Low" and "Linear" control" schemes on Workstation 2. The number of items processed per unit time (hours) is selected as appropriate KPI to reflect performance requirement. According to this figure, total process time in "Linear" control is longer than "High-Low" control. In the present case study average process times are approximately 9.5 and 10 for "High-Low" and "Linear" control, that lead into 0.16 and 0.17 items per minute for the two scenarios, respectively. On energy efficiency only, linear model performs better, but taking into energy-performance as our main indicator, high-low control would make more sense depending on the production requirements. For example for a a daily demand of 150 units, the Linear control scheme may pose risks for having unsatisfied demand. However, for lower demand rates such as 100 units, switching to energy saving control seems a plausible choice for facility owner. Tables 1 - 3 give Energy and Performance interdependencies for the nodes in "Industrial Process" and HVAC unit in technical services area of our example. The experimental data is

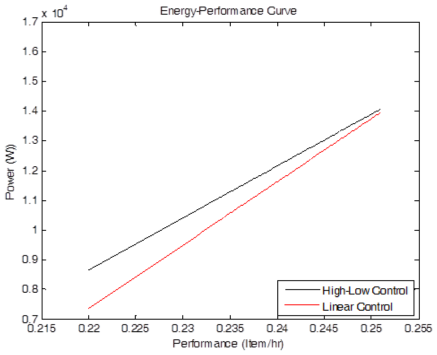

Figure 5 - Energy-Performance curves for High-Low and Linear Controls

obtained from the simulation runs using fictitious data of the two digital twins. This result suggests negative energy consumption interdependencies between the three workstations.

Moreover, energy saving solutions at workstations seem to adversely impact individual stations' throughput; therefore, one needs to take into account throughput requirements when making decisions on implementing energy reduction at machine level. Furthermore, clear dependencies are noticed between energy usage of electric chiller and boiler with fan during cooling and heating seasons, respectively. That is, each unit reduction in fan's energy consumption, results in about 1.2 kWh reduction (i.e. $\delta_{13} = 1.2$) and 8.25 kWh increase (i.e. $\delta_{23} = -8.25$) in chiller's electricity and boiler's gas consumption, respectively. Table 2 shows that daily productivity of industrial system's employees degrade by about 2% per unit electricity saving in chiller during cooling season (i.e. $\delta_{41} = -0.02$). Optimal productivity is achieved at neutral thermal conditions (PMV ≅0). In this case, setback control on chiller modifies room temperature and shifts PMV away from neutral conditions leading to productivity loss. Note however that set back control on HVAC components does not impose high temperature fluctuations in the industrial facility during peak hours in heating season. This explains the small values of ρ for employees in table 2. Potential energy reduction (PER) for nodes is defined according to node-specific technological, physical and economical limitations.

"Energy" Dependency (kWh Per kWh energy saving)			
δ_{ij}	WS1	WS 2	WS 3
WS 1	1.0	-0.53	-0.05
WS 2	-1.46	1.0	-1.09
WS 3	-0.02	-0.75	1.0
"Performance" Dependency (Machine throughout change per kWh energy saving)			
ρ_{ij}	WS1	WS 2	WS 3
WS 1	0.08	- 8.54	-9.57
WS 2	- 0.317	- 9.57	-10.46
WS 3	- 0.238	-9.23	-11.48

Table 2 -"Energy" and "Performance" Interdependency

"Energy" Dependency (kWh Per kWh energy saving)			
δ_{ij}	Chiller	Boiler	Fan
Chiller	1	0	1.20
Boiler	0	0	0
Fan	-0.0026	0	1
"Performance" Dependency (Efficiency change per kWh energy saving)			
ρ_{ij}	Chiller	Boiler	Fan
Chiller	0.08	0	0.002
Boiler	-0.317	0	0
Fan	-0.238	0	0.144
Employee	-0.021	0	0.014

Table 1-"Energy" and "Performance" Interdependency for HAVC – cooling season

Each node has a minimum required performance, which is defined in terms of demand-driven system throughput for the three workstations. As for the HVAC components, η parameters are defined in terms of efficiencies so as to ensure facility temperature complies with set points defined by ASHRAE standards. In other words, energy saving through operational scheduling is acceptable as long as average temperature stays above the required temperature set points by ASHRAE standard.

Assuming the facility owner has a 3% daily energy saving requirement, Table 4 summarizes optimization outputs for the industrial facility in cooling and heating seasons respectively. Cost and penalty coefficients are defined based on average unit prices for electricity and gas in Chicago, IL. As illustrated in figure 6, machine 1 takes the highest share of energy saving (up to 30%) on the industrial process. This translates into up to almost 3700 kWh electricity reduction annually. Chiller and boiler get approximately 13% and 12% daily energy saving in cooling and heating seasons using a set back control. Implementing a combination of the aforementioned

"Energy" Dependency (kWh Per kWh energy saving)			
δ_{ij}	Chiller	Boiler	Fan-Heating Season
Chiller	0	0	0
Boiler	0	1	-8.25
Fan	0	-0.016	1
"Performance" Dependency (Efficiency change per kWh energy saving)			
ρ_{ij}	Chiller	Boiler	Fan-Heating Season
Chiller	0	0	0
Boiler	0	0.00002	0.00002
Fan	0	- 0.0023	-0.0023
Employee	0	0.0003	0.0003

Table 3 -"Energy" and "Performance" Interdependency for HAVC – Heating season

energy saving solutions according to the output of optimization, can lead to a 7% reduction in industrial system’s energy usage.

Nodes	Cooling Season		Heating Season	
	Reduction share (kWh)	Energy Saving (%)	Reduction share (kWh)	Energy Saving (%)
M1	10.4	30	10.4	30
M 2	0.8	2	0.8	2
M3	0.004	0.1	0.004	0.1
Chiller	58.0	13	0	0
Boiler	0	0	86.9	12
Fan	3.2	11	4.1	14

Table 4 – Optimal share of nodes in energy reduction

Conclusion and Future Work

In this article we presented models to optimize energy efficiency in an industrial system using a network approach. The optimization model takes into account the interdependencies between nodes of the network in terms of “Energy Consumption” and “Performance”. We also introduced the concept if “Energy-Performance” curves which can assist the owner achieve energy saving while maintaining performance of nodes in desired levels. The energy efficiency problem is formulated as a general network optimization problem and a solution methodology is presented using an illustrative case study. EnergyPlus simulation package and other simulation tools are used to obtain data for facility’s building and industrial process. Data derived from such simulated metering is used to compute nodes’ interdependencies. The energy efficiency optimization also considers worker productivity and comfort issues. It is assumed that a set of feasible alternatives are given for energy efficiency at each node of the network. The generalization of the approach based on a larger set of feasible alternatives will be an extension to this work. Incorporating the “Energy-Performance” curve in investment, compliance and process risk analysis is also investigated as a future fork for this research.

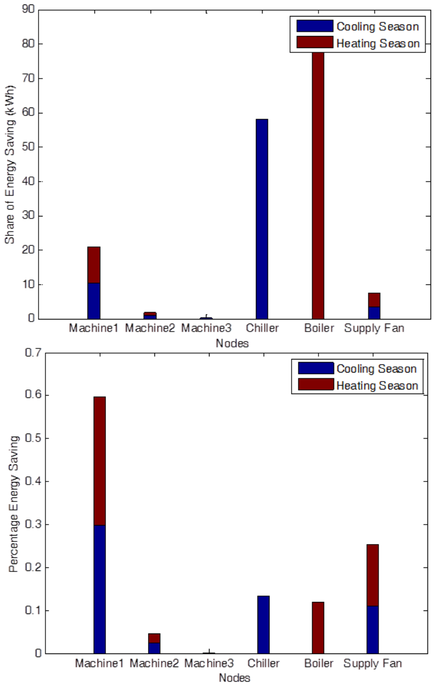

Figure 6 - – Optimal share of nodes in energy reduction

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