Network Modelling with Digital Twins for Energy Efficient Industrial Systems

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Laboratory for Energy Smart Systems (LESS) at Rutgers University

The Laboratory for Energy Smart Systems (LESS) is a multidisciplinary research and resource center that brings together seasoned academic and industry experts in distributed energy resources (DER) and demand side management (DSM).

LESS works with public agencies, private industry, and communities to build sustainable and resilient energy solutions and smart communities, primarily by using technology and predictive and optimization analytics.

Our team also works with the energy sector to develop value-based metrics and practices that will help measure energy efficiency, not only in terms of savings in costs and reductions in carbon footprints, but also increased productivity and performance.

4 faculty members

17 PhDs already graduated from the lab.

3 current PhDs in the lab.

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Problem Statement

What do we want to do?

To formulate industrial energy efficiency as a network optimization problem.

Why?

To distribute achieve energy efficiency across various nodes in the network; to determine the fair share of each contributing node in the system; To create a collective and collaborative approach to energy efficiency.

How?

An optimization and digital simulation framework that models and captures the dynamic interdependencies between nodes in terms of “Energy Consumption” and “Performance”.

Contributions?

An integrative approach (buildings and industrial processes) and taking into account interdependencies between processes and services. We use a production system for demonstration. The idea is general and can apply to any system that includes interrelated processes and facilities.

Technical Approach

Network Description

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.

The total energy reduction due to a mitigation action taken at a node is the sum of *Direct* and *Indirect* effects.

Nodes have “Performance” interdependencies; therefore, energy reduction in one node might improve or degrade the performance in another node (measured in some KPIs).

The balance between energy efficiency and performance (which quantifies both productivity and waste) is accounted for.

The optimal solution ensures that performance, human comfort (in service areas) and other constraints are not violated.

Input Data Requirements & Objective function

Economic reward and penalty data;

Nodes' minimum "Performance" requirements (η_j);

Maximum potential energy saving technically and economically viable for each node (PER_j);

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.

The objective function, is the sum of the profits obtained through Direct and Indirect energy reduction at each node which is stated as:

$$\text{Max} \left\{ \sum_{j=1}^{n} \underbrace{(v_j c_j)}_{\text{Direct reductions}} x_j + \sum_{j=1}^{n} \underbrace{\left(\sum_{i \neq j=1}^{n} (v_i - p_i)\, \delta_{ij} + \sum_{i \neq j=1}^{n} (r_i l_i)\, \rho_{ij} \right) x_j}_{\text{Indirect reductions}} \right\}$$

Model constraints

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

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

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.

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

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.

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

•

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

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

Model Constraints

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.

$$\sum_{j=1}^{n} \rho_{ij} x_j + PRF_i \geq \eta_i \quad \forall i = 1, \ldots, n$$

This equation 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.

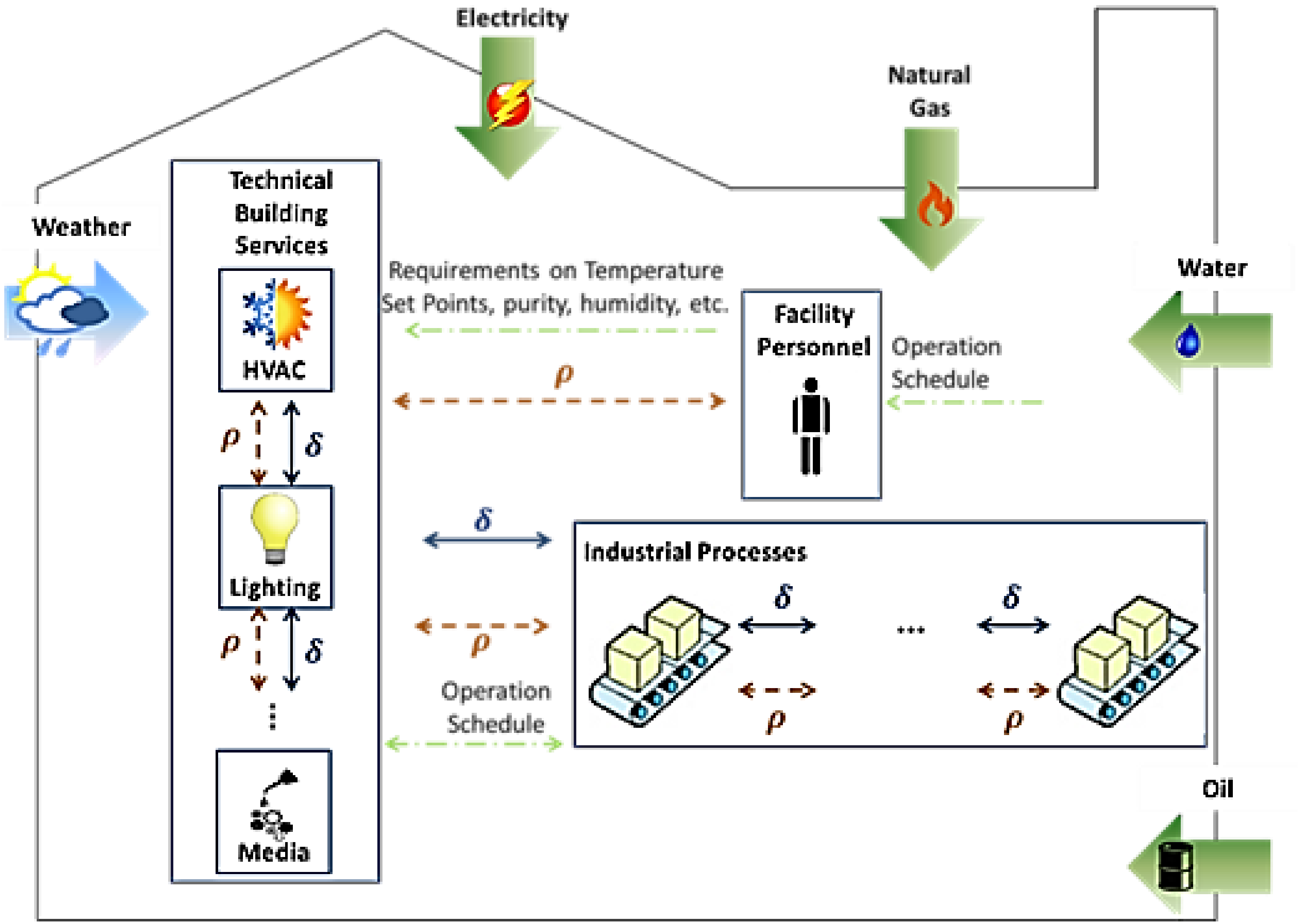
To expand on this idea, we introduce what we call “*Energy-Performance*” curves, which show the direct relationship between energy use and an important KPI of an industrial system (e.g., system throughput rate measured in number of units, number of production batches, or production volume).

In practice, “Energy-Performance” curves are quantifiable from historical data, simulations and/or process monitoring.

Clearly “Energy-Performance” curve for a given process depends on its control, input and output requirements, and system degradation and, henceforth, on maintenance policies and routines which are practiced within the system.

Illustrative Example with two major components:

Industrial process
& Facility



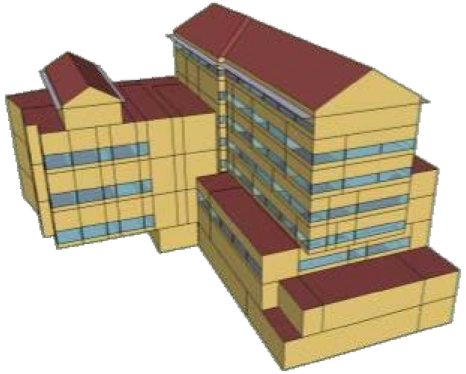
Illustrative Example

Illustrative network has two groups of nodes:

- Industrial Processes – production process; waste management process; etc.

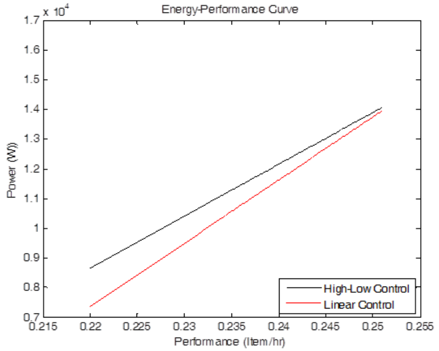
- Technical Services in the facility's building - We focus on HVAC (Heating, Ventilation and Air Conditioning) system as one of the most important components of technical services in our industrial facility. The components of HVAC system studied here are (1) electric variable speed chiller, (2) hot water boiler and (3) electric supply fan.

- EnergyPlus simulation is used to obtain energy data for HVAC. Data derived from such simulated metering is used to compute nodes' interdependencies.

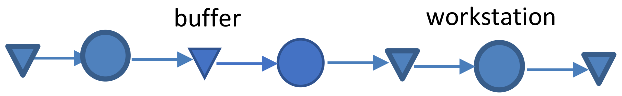


- The energy efficiency optimization considers worker productivity and comfort issues. It is assumed that a set of feasible alternatives are given for energy efficiency at each node of the network.

- We make use of "Energy-Performance" curves to assist the owner achieve energy saving while maintaining performance of nodes in desired levels.



Illustrative Example



Tandem System Configuration

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

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

$\underline{\omega} = (\omega_1; \omega_2; \ldots; \omega_j \ldots)$; 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:

$$\omega_j \cong \{\varphi_j, \psi_j, \zeta_j, \chi_j, \theta_j, \beta_j\}$$

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

Where π () is energy usage function and is measurable in many practical applications. This function depends on the way the process is controlled. Can be measured from historical data or from digital simulations.

Illustrative Example - Dependencies

Energy usage and performance data are used to derive interdependencies between nodes (δ_{ij} and ρ_{ij}). Energy dependency is defined as:

$$\delta_{ij} = \frac{E_i - E_i'}{E_j - E_j'}$$

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;

Performance dependency is defined as:

$$\rho_{ij} = \frac{PM_i - PM_i'}{E_j - E_j'}$$

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.

Dependency between thermal conditions and human productivity:

$$RP = 1.6PMV^5 - 1.55PMV^4 - 10.4PMV^3 + 19.23PMV^2 + 13.4PMV + 1.87$$