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System Approach for Building Energy Conservation

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Abstract

Energy use in residential and commercial buildings and towers represents more than 30% of energy consumption. The increase in number of buildings and towers in most of the major cities worldwide led to several initiatives for energy conservation programs with the main objective to achieve energy savings. Most energy strategies include energy conservation beside the increase in the penetration of renewable energy technologies. This paper shows business model and engineering design framework for practical implementation of energy conservation in buildings. Key performance indicators are modeled and used to evaluate energy conservation strategies and energy supply scenarios as part of the design and operation of building energy systems. The proposed system approach shows effective management of building energy knowledge on the basis of Energy Semantic Networks (ESN), which supports the simulation, evaluation, and optimization of several building energy conservation scenarios. Case study hotel is used to illustrate the proposed building energy conservation framework.

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Keywords: Building Energy Conservation; Energy Semantic Networks (ESN); Building Energy Simulation; Risk-Based Life Cycle Assessment.

1. Introduction

Energy represents power, heat, material, and work to produce product and service. The amount of wasted energy in production and societal facilities represents high percentage that reaches in some cases up to 20% of total energy consumption. Residential and commercial facilities have a number of energy supply options. Energy resources are

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getting smaller when compared with the increase in world population and the associated industrialization that consumes the energy [1]. Fig. 1 shows the forms of energy as thermal, electricity, fuel, and work.

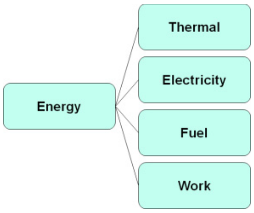

Fig. 1. Energy Reference Model

Although a number of current research project have addressed issues such as; new/alternative sources of energy [2], energy conservation [3] and energy supply management techniques [4], a steady state in terms of "available energy resources-supplies-consumptions" has not yet been reached and may not be reached unless newer and more efficient energy sources/resources are discovered. It is important to find comprehensive research and development in the areas of energy conservation and energy supply management beyond current efforts in renewable energy sources, and energy efficiencies. Energy conservation should address all forms of energy as shown in fig. 1.

Most modern and world class organizations legitimately claim achievements in energy conservations based on implementing techniques, methods and technologies recommended in the literature [5]. Although reasonable achievement levels have been reported in terms of life cycle costing and environmental impacts, the need for continuously looking for newer ways of energy conservation can never be overemphasized. Cutting down a facility's energy use and the right balance between supply and demand can go a long way in conserving energy. Although a number of possibilities are, theoretically, energy responsibilities in particular (a) energy savings, (b) energy conservations and (c) an acceptable supply-demand match ratio require more than just observing a list of dos and don'ts prescribed in the public literature. It requires a new way of thinking, which if implemented will lead to significant energy savings, energy conservation and an acceptable supply-demand match ratio in using the energy. In the proposed research, a unique way of addressing energy responsibilities within industrial facilities will be based on a combination of two paradigms: i.e. (i) a risk based approach to energy responsibilities and (ii) science based approach to energy responsibilities. Thus, it is postulated that energy savings, energy conversation and energy supply management can be looked at in the spirit of "quality by design". Consequently, a novel methodology for energy saving, energy conservation and energy supply management will be designed and developed based on a novel integration of risk-based and science-based analytical techniques. In addition, this methodology will simultaneously address industrial facility carbon footprints which may arise as proponents of activities for matching energy supply and demand ratios. This will reduce environmental impacts of CO2 inherent in conventional energy sources and associated health, environmental and health negative impacts. This requires intelligent and sophisticated tools to capture energy related knowledge from existing processes and facilities. In addition, it is desirable to provide modeling and simulation tools that evaluate different design and operation scenarios to optimize energy use and supply across the facility. Current technologies include power, current, and voltage measurement as well as energy / exergy balance equations at the process level. In addition, measurements are available for heat emission and light intensity in different parts of an industrial facility. Since all these components can be measured and managed, it is essential to build energy models that can represent all these components and be able to simulate different design and operational change scenarios commensurate with optimal energy use and supply. In this regard, operational excellence, through an intelligent operation support system, can help in reviewing, improving/upgrading corporate/site energy utilizations and energy management programs. More than 40% of the energy used in most cities is used to heat or cool buildings [1]. Technologically, it is estimated that with careful consideration and implementation of building energy management systems (BEMS), energy consumption in building sector can be saved up to 20% [2]. BEMS are generally used to manage building energy in three areas. Effective control strategy for energy-related resources inside a building like heating, ventilation and air condition (HVAC), lightening, electrical equipment, lifts, escalators etc. Improvement in efficiency for energy-related resources [3, 4] and efficiency of construction material used in buildings [1, 5].

2. Business Activity Modeling of Building Energy Conservation

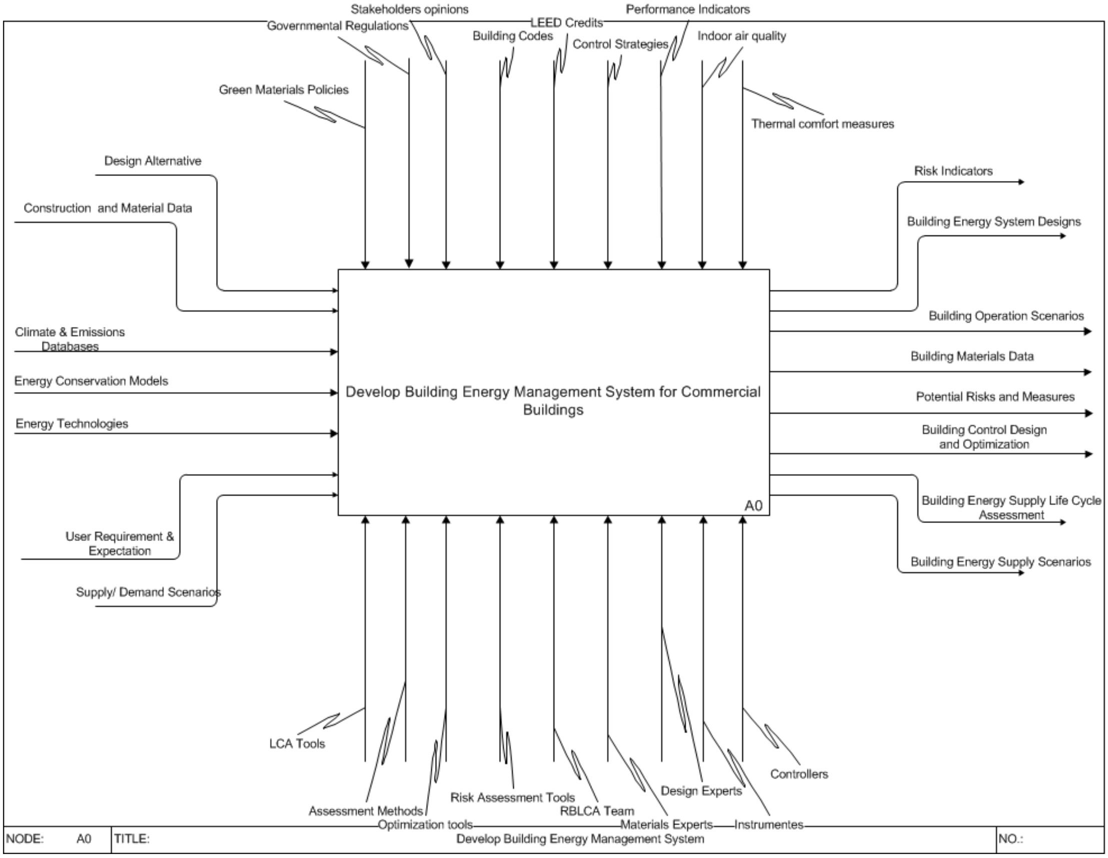

Fig. 2. Energy Conservation Business Activity Model – Top Level

The implementation of building energy conservation strategies requires clear business model that can support the implementation of design and operation of energy conservation in buildings. IDEF0 is commonly used to model business activity models with inputs, outputs, controls, and methods. The hierarchical representation starts with level 0 or top level as shown in fig. 2. Inputs include building design / envelop emission data, energy conservation models, user requirements, climate, energy supply models, and building energy technologies. Outputs will include energy conservation strategies, performance indicators, load profiles, risk assessment and LCA/LCC of energy supply technologies, and control design and optimization. The controls for this top level will be corporate, governmental, national, and international energy conservation regulations and environmental policies, LEED specifications, performance indicators, and material availability.

3. Building Energy Conservation and Management Framework

Based on the activity modeling, there is an integrated approach to achieve building energy conservation by integrating building engineering design with its operation. This can be accomplished by adopting integrated building energy conservation system approach. The integrated solution is based on these top level energy conservation tracks: (a) improve building design and envelop performance improvement of energy supply systems; (b) reduction of energy losses in energy loads and supply infrastructures, as well as technologies; and (c) Improve and optimize building operation and controllers, and behavioral changes, which include policy changes.

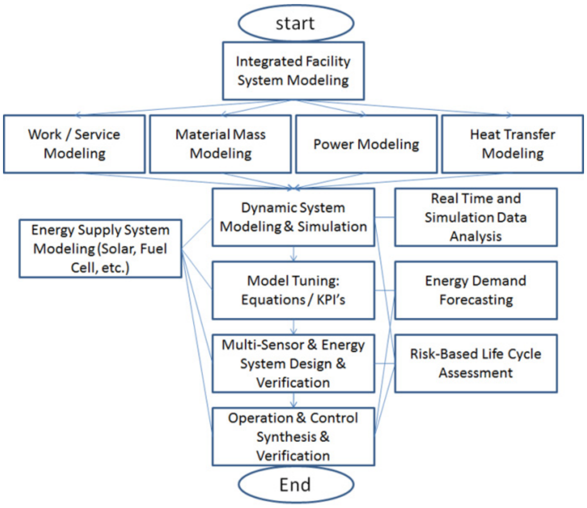

Fig. 3. Energy Conservation and Management Framework

The proposed framework can be described using the system flowchart as shown in fig. 3. The proposed framework is based on modeling the target building using EnergyPlus (or similar tools) where building envelop and associated energy systems are modeled with static and dynamic model parameters with accurate identification of building energy states using energy semantic networks (ESN). Define energy conservation model libraries and associate with each component of the building and define along with KPI's to evaluate the different synthesized energy supply scenario. Multi objective optimization algorithm is used to identify the most optimum energy conservation strategy in terms building envelop and energy supply systems design and operation. The optimized operation scenarios are defined and mapped to the distributed controllers with building systems such as HVAC, boiler, light, elevators, machines, etc. Loads from fuel, thermal, and power as well as water are analyzed individually and the interrelation among each other with accurate load demand forecasting that is used to optimize building energy use in view of energy supply systems, which are evaluated using risk-based lifecycle assessment and costing. For example, life cycle assessment are conducted on gas and power grid components and associated cost and overall emission are estimated for each scenario, and reflected to building envelop design options, operation scenarios, and the associated control parameters are optimized.

3.1. Energy Semantic Network (ESN)

The proposed modeling of building energy systems is based on energy semantic networks (ESN), where energy nodes are used to represent energy storage, generation, conversion, or transportation. Each node is associated with a component or a physical component in the building, as explained by Gabbar (2009). KPIs are modeled and associated with each energy node, in static and dynamic ways, which facilitates the evaluation of energy performance for each design and operation scenario. Energy conservation is strategies are evaluated using the predefined KPIs and optimized with the optimization algorithms. ESN is implemented in knowledgebase where each node represents physical system component associated with its internal energy (storage, conversion, transportation). This includes all types of energy: thermal, electricity, fuel, and work. This is reflected into water, material, environment, and systems. Each node can be connected to other nodes in the form of energy transportation via energy ports, and associated parameters. For example, walls are represented in one node and connected to environment as another node where heat transfer between them is represented in the arc between the two nodes.

3.2. Building Energy KPI Modeling

In order to precisely evaluate different design and operation scenarios for building energy systems, it is essential to model KPIs and associate with building physical modelling. KPI models are based on existing mathematical formulation of KPIs from past research [1; 6–7; 12], as well as the formulation of new KPIs.

A. Economical KPIs

Economical KPIs include operational and maintenance costs of a building. Total operation and maintenance cost of energy resources in a building can be calculated as

$$C_{ann\_op} = \sum_{h=1}^{8760}\sum_{i=1}^{n}[k_{f_i} \times P_i(h) + k_{m_i} \times P_i(h)]. \qquad (1)$$

Where, C_{ann_op} is annual operation cost of the energy resources in the building, k_{f_i} is fuel cost of i^{th} unit ($/kWh), k_{m_i} is the average periodic and reactive maintenance cost of i^{th} unit ($/kWh), and $P_i(h)$ is the power consumed by the i^{th} unit.

B. Environmental and Reliability KPIs

Environmental KPIs include, water conservation, greenhouse gas (GHG) emission, materials, durability, waste, safety, and environmental risk factors. The reliability KPIs include operational reliability of building energy resources including condition based maintenance indicators, remaining useful life predictors, and equipment power factors. Reliability gives an indication of how a system performs without any maintenance. The reliability indicators include maintainability, operational availability, functional availability, and decision capability. The calculations of these KPIs are out of scope for this paper.

C. Quality KPIs

Quality KPIs include CO2, humidity, and individual dissatisfaction index. The CO2 concentration for an energy zone can be calculated as [10]

$$\rho_{air} V_z C_{CO_2} \frac{dC_z^t}{dt} = \sum_{i=1}^{N_{sl}} kg_{mass_{sl}} \times 10^6 + \ldots$$
$$\sum_{i=1}^{N_{zones}} \dot{m}_i \left(C_{zi} - C_z^t\right) + \dot{m}_{\inf}\left(C_\infty - C_z^t\right) + \dot{m}_{sys}\left(C_{\sup} - C_z^t\right). \qquad (2)$$

Where, $\sum_{i=1}^{N_{sl}} kg_{mass_{sl}}$ is sum of scheduled internal carbon dioxide (CO2) loads, the term 10^6 is used to make the units of CO2 as parts per million (ppm), $\sum_{i=1}^{N_{zones}} \dot{m}_i \left(C_{zi} - C_z^t\right)$ is CO2 transfer because of inter-zone air mixing and can be expressed as ppm-kg/s, C_{zi} is CO2 concentration in zone air as ppm, $\dot{m}_{\inf}\left(C_\infty - C_z^t\right)$ is CO2 transfer because of infiltration and ventilation and is expressed as ppm-kg/s, C_∞ is CO2 concentration outdoor air as ppm,

$\dot{m}_{sys}\left(C_{\sup}-C_z^t\right)$ is CO2 transfer because of system supply as ppm-kg/s, $C_{\sup}$ is CO2 concentration in system supply air as ppm, $\dot{m}_{sys}$ is air system supply mass flow rate as kg/s, $\rho_{air}V_z\dfrac{dC_z^t}{dt}$ is CO2 storage term in zone air as kg/s, C_z^t is zone air CO2 concentration at current time stamp as ppm, ρ_{air} is zone air density as kg/m^3, V_z is zone volume as m^3, and C_{CO_2} is CO2 capacity multiplier. The humidity factor for an energy zone can be calculated as [10].

$$\rho_{air}V_zC_W\frac{dW_z^t}{dt}=\sum_{i=1}^{N_{sl}}kg_{mass_{sl}}+\dots$$
$$\sum_{i=1}^{N_{surfaces}}A_ih_{mi}\rho_{air_z}\left(W_{surfs_i}-W_z^t\right)+\sum_{i=1}^{N_{zones}}\dot{m}_i\left(W_{zi}-W_z^t\right)+\dots$$
$$+\dot{m}_{\inf}\left(W_\infty-W_z^t\right)+\dot{m}_{sys}\left(W_{\sup}-W_z^t\right). \qquad (3)$$

Where, $\sum_{i=1}^{N_{sl}}kg_{mass_{sl}}$ is sum of scheduled internal moister loads, $\sum_{i=1}^{N_{surfaces}}A_ih_{mi}\rho_{air_z}\left(W_{surfs_i}-W_z^t\right)$ is convection to zone surfaces, $\sum_{i=1}^{N_{zones}}\dot{m}_i\left(W_{zi}-W_z^t\right)$ is moisture transfer due to multi-zone airflow and can be expressed in kgWater/s, W_{zi} is humidity concentration in zone air in kgWater/kgDryAir, $\dot{m}_{\inf}\left(W_\infty-W_z^t\right)$ is moisture transfer because of infiltration in kgWater/s, W_∞ is moisture concentration of outdoor air in kgWater/kgGryAir, $\dot{m}_{sys}\left(W_{\sup}-W_z^t\right)$ is moisture transfer because of system supply, $\dot{m}_{sys}$ is air system supply mass flow rate in kg/s, $W_{\sup}$ is moisture concentration in system supply air in kgWater/kgDryAir. W_z^t is zone air moisture concentration at current time stamp in kgWater/kgDryAir. The degree of individual dissatisfaction index (DID) can be calculated as [11]

$$DID=\frac{1+\tanh(2\left|vote\right|-3)}{2}. \qquad (4)$$

Where, is

$$vote=\begin{bmatrix} +3 & T>T_o+2\Delta T \\ -3 & T<T_o-2\Delta T \\ 1.5\dfrac{T-T_o}{\Delta T} & Otherwise \end{bmatrix}. \qquad (5)$$

Where, T_o is set point or desired temperature in ^{o}C, T is current temperature in the room and ΔT is individual's temperature tolerance.

4. Case Study Building Energy Modeling

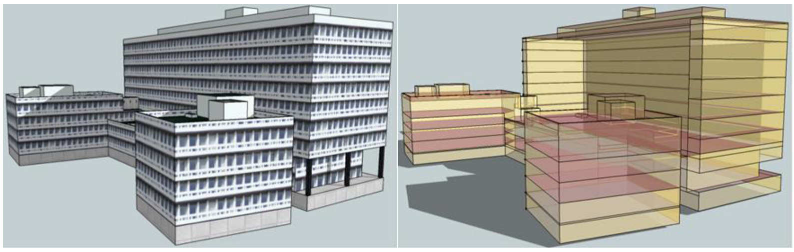

Fig. 4. Case Study Hotel

To demonstrate the proposed framework, a hotel is used as a case study, as shown in fig. 4.

Table 1: Properties of Materials

Material Types	Conductivity (W/m.K)	Density (kg/m^3)	Specific Heat (J/kg.K)
100mm Brick	0.89	1920	790
200mm Heavyweight concrete	1.95	2240	900
25/50mm Insulation board	0.03	43	1210
19mm Gypsum board	0.16	800	1090
Metal surface (0.0008 m)	45.28	7824	500
100mm Lightweight concrete	0.53	1280	840
Acoustic tile	0.060	368	590
25mm Wood	0.15	608	1630

After modeling the building in EnergyPlus, building energy state variables are collected and identified KPI's are evaluated for different components of the building, and associated energy supply systems. Performance indicators are modeled in terms of functionality, environment, safety, and cost. Table 1 shows sample of selected KPIs for functionality. The evaluation of these KPIs will be conducted on each energy conservation design and operation scenario, as well as with control parameters to ensure optimum energy saving, with the considerations of energy supply systems, loads, and infrastructures. Table 1 shows the selected building materials modeled within EnergyPlus, while table 2 shows the operational costs as well as GHG emissions.

Table 2: End Use Building Operational Costs and GHG Emissions

	Electricity (GJ)	Natural Gas (GJ)	Water (m^3)	CO_2 Emission (g)	CO Emission (g)	CH_4 Emission (g)	NO_x Emission (g)	Operational Cost ($) ($0.55/kWh) (1 GJ = 26.13m^3) ($0.15/$m^3$)
Heating	0.00	719.32	0.00	37476.57	28.70	0.762	34.02	2819.37
Cooling	108.44	0.00	0.00	37053.94	12.86	81.02	67.47	16567.0
Interior Lighting	89.52	0.00	0.00	30588.98	10.61	66.88	55.69	13677.0
Interior Equipment	133.59	0.00	0.00	49655.40	15.84	99.81	83.11	20410.0
Fans	11.50	0.00	0.00	3929.55	1.36	8.59	7.15	1756.90
Pumps	84.97	0.00	0.00	29034.24	10.07	63.48	52.86	12982.0
Heat Rejection	44.52	0.00	721.72	15212.48	5.28	33.26	27.70	6801.7
Total	472.54	719.32	721.72	202951.16	84.72	353.802	328.0	75003.97

5. Building Electric Circuit Modeling

The load profiles of building voltage and current profiles at the point of common coupling (PCC) are shown in fig 5 [13].

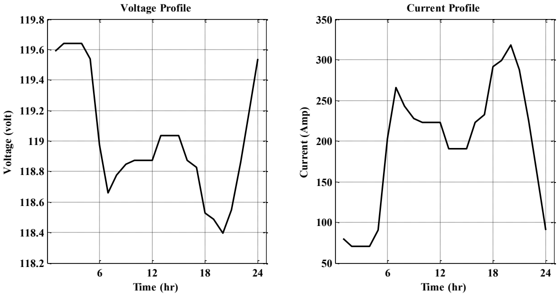

Fig. 5. The voltage and current profiles of the large hotel at PCC

In order to ensure accurate simulation results of building thermal and electrical energy, a comparison between energy consumption from EnergyPlus and Matlan simulation is conducted, as shown in fig. 6, which reflects the accuracy of the developed energy models in Matlab compared with results obtained from EnergyPlus.

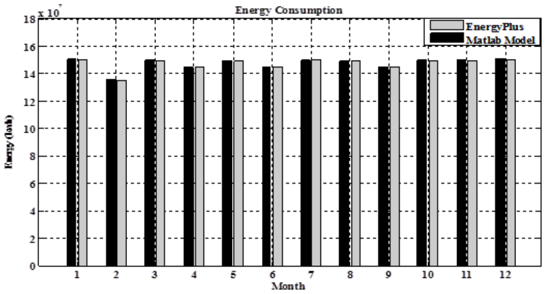

Fig. 6. Comparison between EnergyPlus and Matlab Simulation for Hotel Energy Consumption

There are potential advantages of the proposed building simulation models over EnergyPlus as it provide accurate thermal, electricity, and fuel use and consumption based on dynamic scenario synthesis in view of building loads and energy parameters, which can be applied for different technologies and can offer great flexibility and accuracy. Table 3 show summary energy data for the selected case study building, which provides a better understanding of building energy consumption, GHG emissions, and costs. It reveals that heating costs is higher than cooling costs due to long winter months, compared with summer duration in Canada. It provides an indication of potential energy conservation if effective energy systems are adopted for building heating and cooling. Proper gas-power technologies can be considered strategic to compensate for such increasing energy demands in buildings.

Table 3: Hotel Energy Data Summary

Building Model Element	Estimated Value
Electrical: **Yearly Estimation (kWh)** **Estimated Cost ($)**	 480,506.91 59,582.86
Thermal Cooling: **Yearly Estimation (kWh)** **Estimated Cost ($)**	 189,216 23,462.78
Thermal Heating: **Consumption of Natural Gas (m^3)** **Estimated Cost ($)**	 217,314.97 53,802.17
CO_2 Emissions (metric tons)	386.81
Initial Cost Total ($)	N/A

6. Conclusions

This paper shows a system approach for building energy conservation and management where activity models are identified using IDEF0 for practical implementation in target buildings and the associated design and operation support tools. Energy conservation framework is defined which comprises modeling building energy in the forms of thermal, fuel, and electricity and link to materials. Define KPI's for each building model element and evaluate in view of energy conservation strategies and their mapping to design and operation scenarios. The control parameters are optimized and implemented in distributed control systems for energy supply systems and loads. Data collected from EnergyPlus are compared with real time data collected from real time data acquisition to fine tune energy models and provide accurate estimation of current energy profiles for loads, generation, supply, and efficiency.

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