Energy Consumption Modeling and Analyses in Automotive Manufacturing Plant

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Manufacturing plants energy consumption accounts for a large share in world energy usage. Energy consumption modeling and analyses are widely studied to understand how and where the energy is used inside of the plants. However, a systematic energy modeling approach is seldom studied to describe the holistic energy in the plants. Especially using layers of models to share information and guide the next step modeling is rarely studied. In this paper, a manufacturing system temporal and organizational framework was used to guide the systematic energy modeling approach. Various levels of models were established and tested in an automotive manufacturing plant to illustrate how the approach can be implemented. A detail paint spray booth air unit was described to demonstrate how to investigate the most sensitive variables in affecting energy consumption. While considering the current plant metering status, the proposed approach is advanced in information sharing and improvement suggestion determination.

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1 Introduction and Motivation

All the aspects of human activity require rising support from energy. Among the four end sectors (industry, commercial, residential, and transportation sectors), industry is the biggest energy consumer in the U.S. over the past 60 years. More than 30% of the total energy is used in the industrial activities [1].

As an important part of industrial activities, manufacturers consume a significant amount of energy every year. However, despite the high energy demand, manufacturers are facing pressures from three main aspects: instant cooperation profit, long-term brand image, and policies. The data from the U.S. Energy Information Administration shows that the price of energy has been continuously increasing over the past 15 years [2].Considering the energy prices, types of vehicles produced, and various technologies used in the production processes, the energy cost can range from $38/vehicle to $93/vehicle [2–4]. Shrinking market profit requires the cooperation to cut spends on every aspects including the utility bills.

On the other hand, the correlation between the energy consumption and environmental degradation is well known. In order to maintain a positive brand image, the plants need to use less traditional energy and more clean renewable energy. Finally, the regulations, standards, and laws force the manufacturers to improve their energy efficiencies. Recently, more countries and areas participated in the discussion of policy initiation and implementation [5].

Understanding the energy usage within the manufacturing system is the first step for later improvement. Establishing the energy consumption model of automotive manufacturing plant can be used as an example to illustrate how the modeling approaches can be applied for better knowledge on the energy usage within the plants. However, how to build holistic models within the plants where thousands of production processes were interacted is challenging. To solve this problem, a systematic modeling hierarchy with levels of models that serve different layers of organizational managers and technicians is the key. This paper has proposed the model hierarchy and modeling methods, taking the example of complex automotive assembly plants, and the approach should be able to be repeated for other manufacturing plants. Meanwhile, the approach should be able to provide guidance for the next improvement measurements to save energy.

2 Automotive Manufacturing Plant Introduction and Literature Reviews

This section will begin with the introduction to the framework concept of the manufacturing system, followed with a review on the previous efforts made by researchers on model construction for manufacturing energy usage.

2.1 Framework of a Manufacturing System and Scope. Most manufacturing systems are complex systems containing a potentially large number of subsystems. It is important therefore to clarify the scale of discussion pertinent to the efforts of this work. Fortunately, a rich systematic classification has been recently described. In 2010, Reich-Weiser et al. [6] started from the methodologies for product life-cycle assessment and proposed four levels in spanning the organizational domain (i.e., the product feature level, the machine/device level, the facility/line/cell level, and the supply chain level) and four levels in the temporal domain (i.e., the product design phase, the process design phase, the process adjustment phase, and the postprocess phase) (Fig. 1). In 2012, Duflou et al. [7] further developed the system into five levels in the organizational domain (i.e., the device/unit process level, the line/cell/multimachine system level, the facility level,

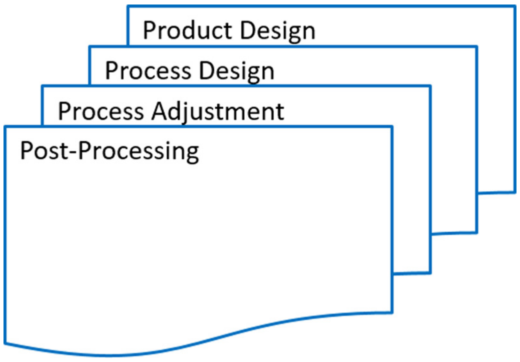

Fig. 1 Energy system in temporal framework (after Ref. [6])

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the multifactory system level, and the enterprise/global supply chain level) (Fig. 2). Unlike Reich-Weiser's team starting from the product life-cycle standpoint, Duflou's team investigated from the viewpoint of the production process system.

This research work focuses on the energy use within the manufacturing plant at the postprocessing phase.

2.2 Manufacturing Energy Models Review. In this section, recent works on different levels of the manufacturing system within the plant level will be reviewed. Main production processes in the automotive assembly manufacturing plant will be discussed, and models of major procedures will be exemplified.

2.2.1 Energy Performance and Benchmark Model. Energy performance models study the plant energy consumption per vehicle. One typical model for energy modeling of automotive assembly plant is from the work of Boyd's in 2005 [8]. Boyd developed a performance-based indicator known as the energy performance indicator (EPI) to score energy performance (in MWh/vehicle) compared with similar plants in the automotive industry based on the source data from 35 plants within the 3 years (1998–2000). Corrected ordinary least squares (COLS) regression stochastic frontier models were established to relate the energy consumption with the productivity (number of vehicles produced), product information (measured through the vehicle wheelbase variable), plant utilization information (plant utilization rate), and weather information (cooling degree days (CDD) and heating degree days (HDD)).

Benchmark models are intended to establish references across a group of similar organizations. Patil and Seryak developed a lean energy analysis (LEA) method which models electricity and natural gas usage in the automotive manufacturing plants [9]. The main contribution of this paper is the generation of *energy signatures*, defined as the *basic shape of statistical regression*. It is used to represent the baseline of energy use in each plant. This paper reported that the *energy signature* is represented by the manufacturers' unique energy equations derived from their own independent variables. It can be used to compare within industrial sectors to determine the best-practice facilities. It is interesting that they point out the concept of the energy signature, which is unique to every plant, according to the authors. However, the claim that the model can be used for comparison is questionable due to its oversimplified multivariable regression with only inputs from local air temperature and production data.

Scavarda et al. developed a product variety multimarket study in the automotive industry [10]. They included an empirical study on many significant passenger car models and conducted a benchmarking analysis by addressing the incoherent results in different countries. Rothenberg et al. compared the different benchmarking approaches in automotive manufacturing environmental performance [11]. They categorized the approaches into the regulatory, gross emissions, efficiency, and life cycle, and found that different companies use different methods in comparison.

The relatively straightforward statistical regression models are used in these reviewed papers. This makes them flexible to be applied to similar manufacturing plants. Also, due to the limited amount of input data required, these models are inexpensive and feasible to use. Nonetheless, their models were insufficient in considering in the various technologies used in the plants. Finally, these models cannot be used in identifying potential improvements.

2.2.2 Systematic Model. Models in different levels provide detail modeling approaches for energy usage within the manufacturing plant, but when it comes to the holistic perspective on energy utility of the plant, they are incompetent in information interaction among levels. An ignorant combination of the current levels of models either loses the comprehensive picture of the plant or lacks accuracy and detail. Therefore, the simple compilation of levels of models could cause problems in decision-making and information dissemination. Systematic modeling in

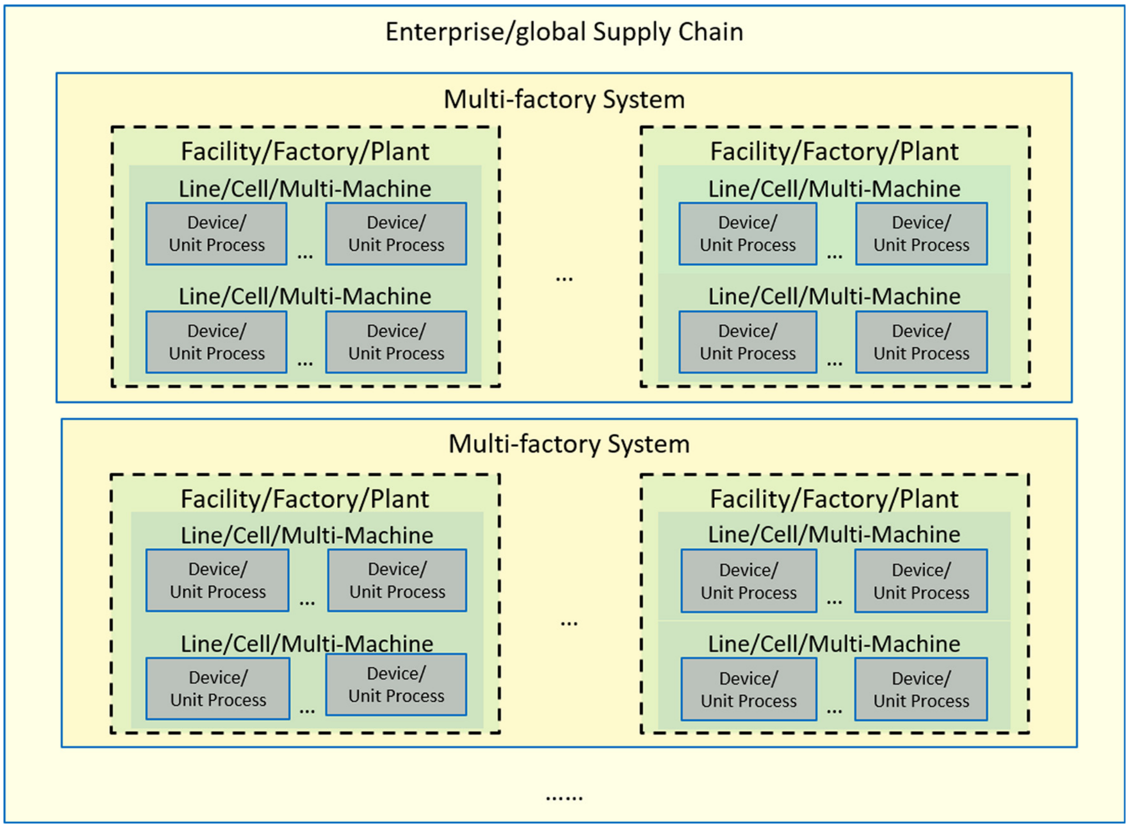

Fig. 2 Energy system in special/spanning organizational framework (after Ref. [7])

compensating for disadvantages caused by levels of modeling is summarized here.

2.2.2.1 Embodied product energy (EPE) *model.* Kara and Ibbotson [12] started from the life-cycle analysis point of view, proposing the methodology in assessing the embodied product energy (EPE). They used two roofing systems (fiber composite and galvanized steel roof systems) as demonstration examples and developed ten different manufacturing supply chain scenarios, and considered the embodied energy of raw materials supplied. The supply chain scenarios considered the transportation types (e.g., road, rail, and ship) and distances, and the raw material embodied energy includes the amount of energy used in previous manufacturing processes. This work includes the multifactory and facility levels. It is good in understanding the embodied energy in the whole product life and the energy consumption in the product's different life stage. However, like many other life-cycle assessment methodologies, it is criticized by its inaccuracy, large variety range in the same product, and lack of detailed description of the production procedures.

2.2.2.2 Discrete event models. Discrete models have the energy consumption in "numbers of product" and usually assume that the energy consumption of one product has no significant difference from another product. Evolved from the traditional EPE models, discrete event simulation models [13,14] took this concept one step further by describing the production procedures. They modeled the energy from two aspects: direct energy (DE) and indirect energy (IE). DE is defined as the energy used directly in the manufacturing process (e.g., welding and machining); and IE is defined as the energy consumed to maintain the working environment (e.g., lighting, heating, and ventilation). DEs were modeled by using physical models of multimachine and single-machine levels, while IEs were calculated as the average energy consumption over the time and number of products stayed in different production zones.

Their model provides better understanding on the production lines and involved the factory, multimachine, and single-machine levels, but it simply sums all the energy in levels without giving it a deep analysis on the influential factors nor showing the interaction among levels of models to compensate the disadvantages of each other. This approach is no more than the compilation of the multimachine and single-machine level models. Besides all the advantages in levels of modeling strategy, this method makes the models cumbersome in application. Furthermore, even though the automotive assembly plants process a discrete manufacturing procedures, the energy utility in the plants is both discrete and continuous. The discrete event modeling approach proposed in reviewed paper neglects the continuous nature of the DE and IE, and the interaction between these two.

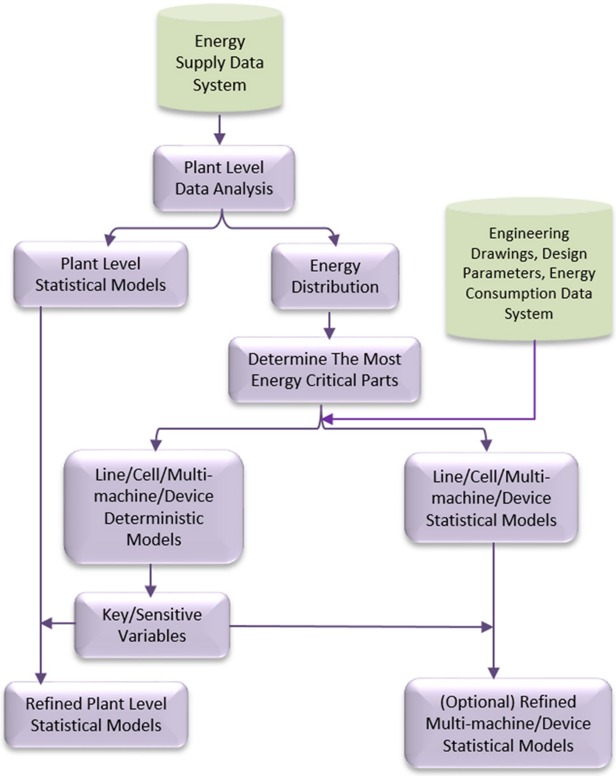

Fig. 3 Flowchart of energy modeling in plant

2.2.2.3 Hybrid models. The importance of the building shell itself and the interaction between the production process and its environment were addressed in Refs. [15] and [16]. In these papers, the energy consumption of technical building services is taken into consideration. They illustrate how it is used to ensure the production conditions in terms of temperature, moisture, and air purity through heating, cooling, and conditioning of the air; and how it is affected by the local climate of the production site and machine waste heat. Unlike the previous EPE and discrete event simulation models, these models also suggested a hybrid approach (combined discrete event and continuous simulation) considering the involvement of continuous building energy and discrete product production. Unfortunately, the involvement of the building energy consumption into the production process was only discussed theoretically. Both papers did not provide the modeling approaches nor quantification of energy consumption from the building heating, ventilation, and air conditioning (HVAC). Also, because both papers still concentrated on the specific simulation models for certain processes instead of system modeling approaches, they also suffered the problem of inflexibility and infeasibility in industrial applications.

3 Modeling Approach

A systematic approach is key for efficient modeling ("efficiency" is defined as information amount, flexibility to apply in similar systems, feasibility to current plants, ability of sensitivity analysis, improvement identification, and accuracy) and for constructing the models at different levels. Unfortunately, the current systematic models reviewed are not sufficient to satisfy these requirements.

Meanwhile, it is noticeable that the disadvantages of high-level models (energy performance models and benchmark models) are the advantages of low-level models (multimachine and machine models). How to use the manufacturing system framework to build models in different levels while considering the ability to interact to each other, as well as the flexibility and feasibility, is the key contribution of this proposed approach.

There are two main approaches to interface the models at different levels: top-down and bottom-up. Top-down is to establish models at a high level first and then drive the detail down to subsystems like multimachine and single device levels. Especially in a complex manufacturing plant, such as for automotive assembly, where the exhaustive low-level models of the comprehensive plant are infeasible, the top-down method can be used to wisely select the critical energy components in the low-level consumption. Therefore, the top-down method is useful in helping selectively spend money and time in establishing models. Bottom-up defines using the information from low level to feedback the high-level models and make high-level models more intelligent and robust, while keeping the advantages of feasibility and flexibility. In this paper, detail top-down approach will be discussed, and a case study of the top-down will be provided.

A general energy modeling and analyzing approach is described in Fig. 3. Usually, a manufacturing plant has a high-level energy supply data system to help understand how much energy is used in total. The first step is to understand the data system. "Are all of the energy sources purchased? Where are the meters that record the data located? Are there any branches?" Questions of the metering and data system need to be made clear before modeling. For plants that lack data systems, either install feasible meters for data collecting or use utility bill information instead. In this stage, plant level statistical models can be built. Regression models correlating the energy consumption with the weather information and productivity or simple time series models with historical data are both good choices. Energy distribution analysis to the departments is a critical part in determining the next level modeling focus. Energy modeling can be processed in parallel. However, in most situations, considering the time and resources required, one area needs to be focused to proceed to the next level model. In this step, meetings, interviews, surveys, and if available meter readings in the multimachine and production lines can be used to determine the concentration of the next step work. After the focusing area is narrowed down, detailed physical models or statistical models can be built based on the data availability. Sometimes, in a case of no meters in supporting the models, extra feasible meters may select to help further validate the model results before any other improvement implementation.

4 Case Study

In this section, a case study from the automotive assembly plant will be used to illustrate how the proposed modeling approach can be implemented. The studied case assembles vehicles from stamped panels and other subassembled components. The plant purchases electricity, natural gas from the utility companies, as well as landfill gas from local supplier. Electricity is used to power the equipment. Natural gas is mostly used for space heating and paint curing. Landfill gas is used on two on-site hot water and electricity generators (combined heat and power (CHP)). Main energy conversion and transmission happen at the *Energy Center*. In the Energy Center, purchased energy from the utility companies will be converted to the energy forms (hot water, chilled water, compressed air, and so on) and amounts the main production area needs (Fig. 4).

The studied plant can be split into two major parts: the energy supply system and the energy consumption system. Energy supply system is located in the *Energy Center*, where all the on-site energy conversion and transmission are processed. The energy consumption system contains all the energy used in the major production departments, which is also the focus of energy modeling approach discussed in this paper.

The framework-guided systematic approach is applied to this case study. An updated scheme specific to the plant is shown in Fig. 5.

First, the plant level models were built to help understand the trends and patterns in energy purchased from the supplier. Linear regression and time series approaches were used at the outset to give a general knowledge on the energy consumption of the whole plant. To efficiently (in terms of cost and time) establish low-level models, plant energy data were further analyzed to determine the energy distribution. Specifically speaking, energy distribution to each production department and low-level multimachine processes was investigated to help decide which parts of the plant are the most critical ones (top-down). Together with the information from production specialist and low-level modeling requirement, low-level models were established.

All the data used in this research work are normalized to protect the confidentiality of the plant.

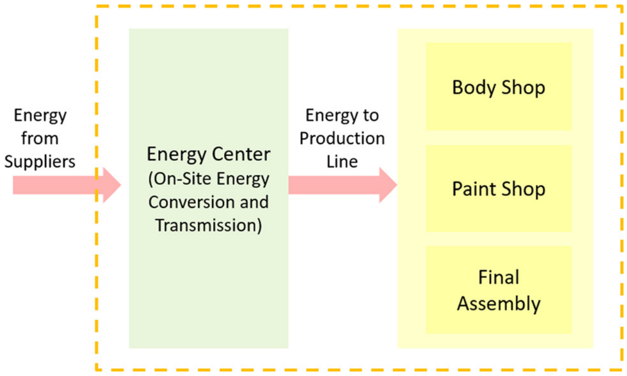

Fig. 4 Energy flow sketch in studied automotive manufacturing plant

4.1 Plant Level.

Monthly energy costs from the utility supplier are the most available data at the plant level. One year of monthly energy bill data were collected. Figure 6 is the monthly plot of the three energy forms purchased from utility companies. Each of them was normalized to monthly average values.

From Fig. 6, it is obvious to observe that the natural gas relationship is a concave second-order, while the electricity relationship is a convex second-order; and the landfill gas trend is relatively stable over a 1-year timeframe. According to the observed shape, quadratic and linear models were fitted as shown in Fig. 7.

Though Fig. 7 shows a good fitting in the modeled 12 months, the model shows a poor accuracy in the next year data (Fig. 8). Also, the fitted models do not provide any information explaining the reasons of energy curves nor any constructive suggestions on energy savings.

The manufacturing plant environment is controlled through an HVAC system. For the most part, heating energy is provided through hot water from natural gas and cogeneration system, and cooling energy is provided through chilled water, mainly from electricity. One of the main causes of fluctuation in the monthly

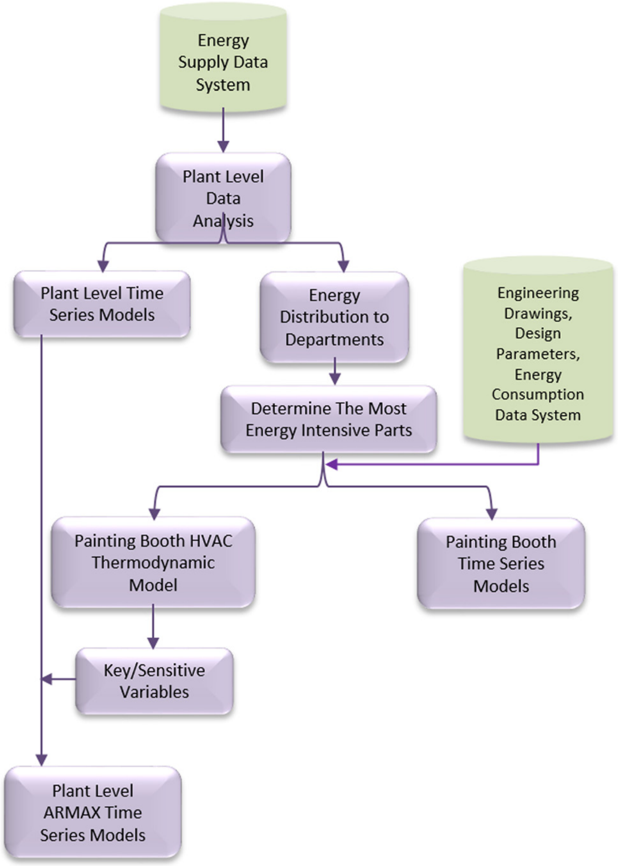

Fig. 5 Framework-guided systematic approach scheme of studied case

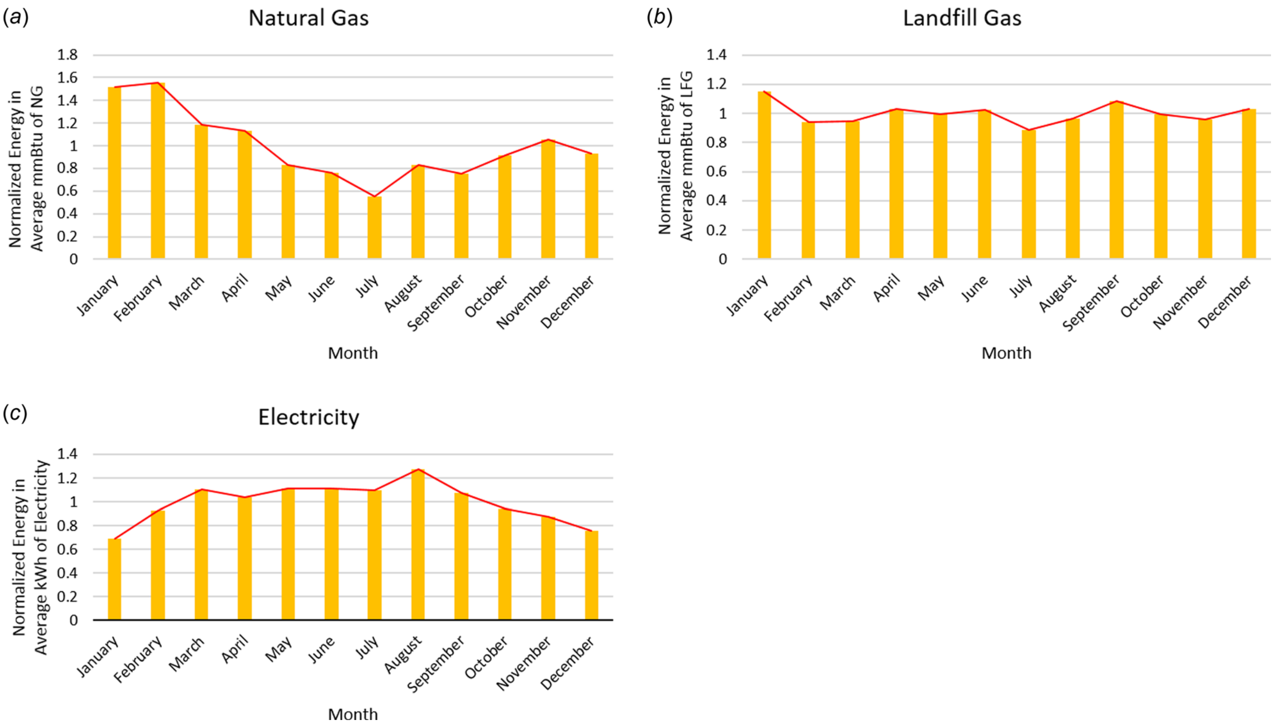

Fig. 6 Purchased natural gas (*a*), landfill gas (*b*), and electricity (normalized) (*c*)

purchased energy is local weather changes seasonally. In the summer months when the weather is hot, the heating energy (hot water) for the plant building is at bottom, but chilling energy (chilled water) for spacing cooling is at peak. In contrast, during the winter months, electricity used for generating chilled water is at bottom, but the natural gas for hot water is at peak. This is one of the reasons, natural gas and electricity show a seasonal trend as in Fig. 6. It is also known that the landfill gas only feed to the gas turbine, which runs the on-site cogeneration system at its full capacity year round. This is the reason why the landfill gas shows a stable linear trend in the studied 12 months.

To include the weather information in the regression model is a good idea to make the model more informed and robust. However, direct including of monthly average temperature is not adaptable,

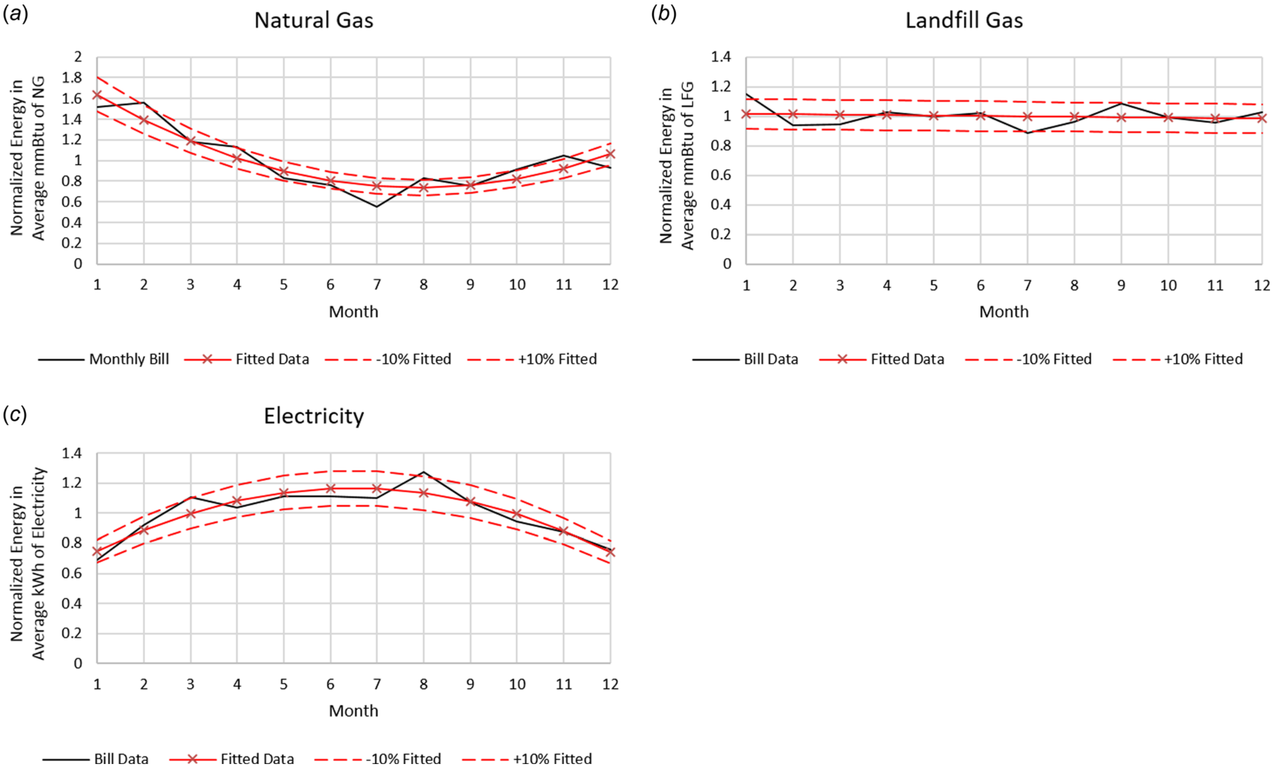

Fig. 7 Fitted natural gas (*a*), landfill gas (*b*), and electricity (normalized) (*c*)

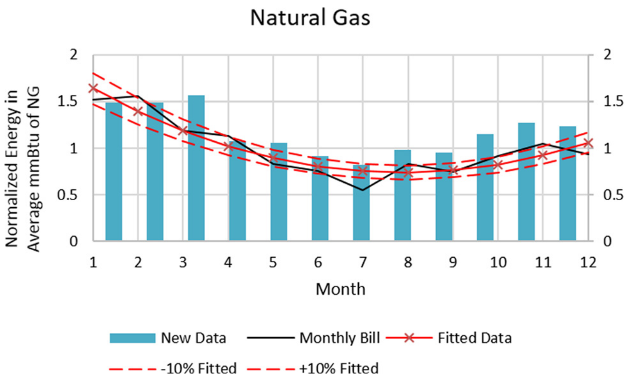

Fig. 8 New year data with fitted model—natural gas example

since it averages out the weather changes that represent the demand for heating and chilling. Heating degree days (HDD) and cooling degree days (CDD) can be used. Heating degree days represent the summation of degrees above the 65 °F in a month, while cooling degree days represent the summation of degrees below the 65 °F in a month. These two variables are widely used in building energy calculation. Figure 9 illustrates the modeling results.

The regression model of the natural gas and electricity correlated purchased energy with weather information (HDD and CDD)

$$E = c + a_1 \times \mathrm{CDD} + a_2 \times \mathrm{HDD} \tag{1}$$

In Eq. (1), E represents the natural gas or electricity, c is the constant value, and a_1 and a_2 are the parameters. However, unlike expected previously, the electricity has negative parameters with both HDD and CDD, i.e., $a_1 < 0$ and $a_2 < 0$ while E is the purchased electricity.

Though regression models can be used to describe the energy at plant level, it cannot provide any information on the reasons why inputs affect the energy.

Energy distribution at the trunk level is a good method to help select critical parts in the plant and make the low-level modeling and analysis more efficient.

Through the energy supply data system, total energy for each department was analyzed in different forms of energy carriers. The energy forms include: hot and chilled water for building and process environment control, natural gas for building and process heating and paint curing; compressed air, and electricity for power equipment and tools. To protect the confidentiality of the studied case, the approximate percentages of each energy form are shown in Fig. 10.

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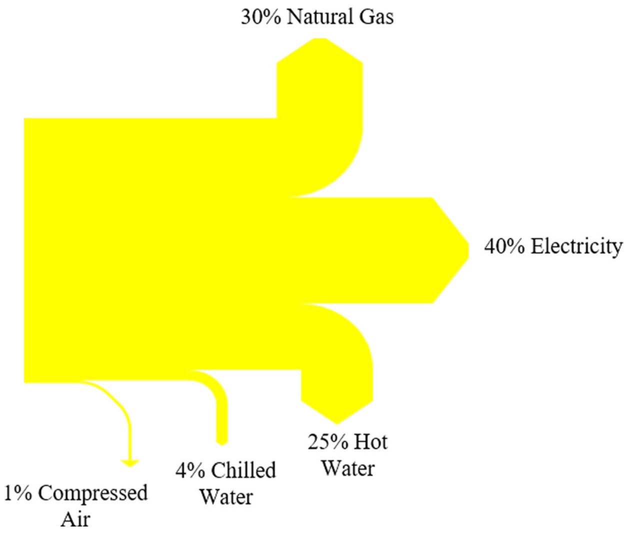

Fig. 10 Energy distribution in energy forms

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The distribution results (Fig. 11) indicate that the most energy intensive department is paint shop. Further discussions and investigations were developed inside of the paint shop. Potential energy saving suggestions were made for implementation. Later on, the improvement areas were decided based on holistic consideration

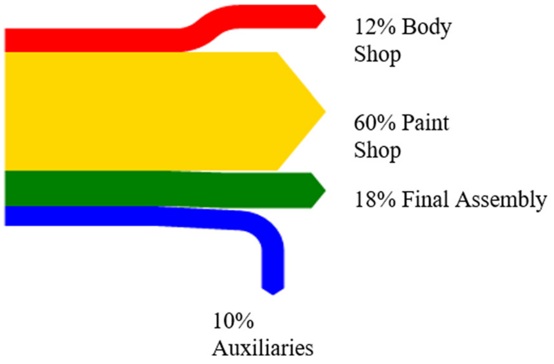

Fig. 11 Energy distribution to department

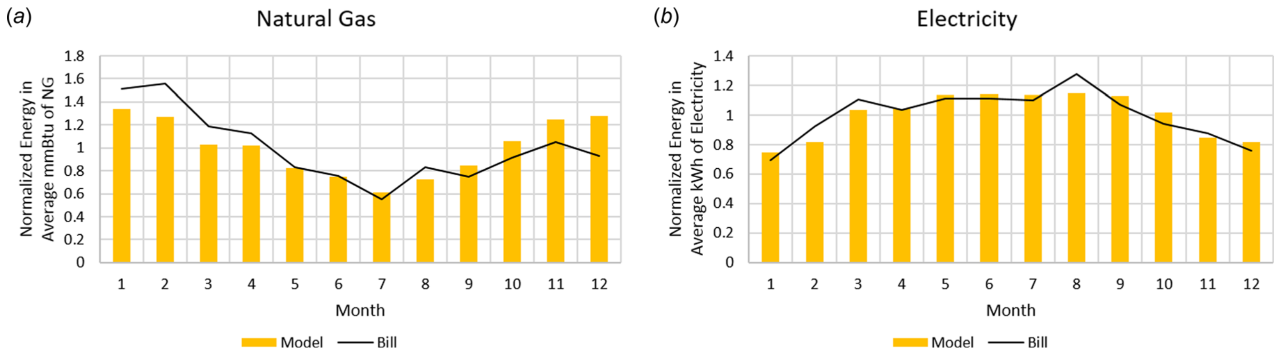

Fig. 9 Regression model: (a) natural gas and (b) electricity

of time, monetary cost, and influential on the production and workers. The painting booth responsible for the basecoat painting spray was selected for further study.

4.2 Low Level.

Painting spray booths are small separate rooms isolated from the painting building to prevent particle matters and gases like volatile organic compounds (VOCs) from paint to release into the working environment. Meanwhile, the painting spray processes require controlled temperature and humidity to provide a high-quality finish. It needs certain amount of air blowing from the roof of the booth to collect the sprayed paint and prevent residuals from affecting the next coming vehicles. It is known that the energy used in air conditioning to maintain the booth environment is huge.

In the air supply units to paint spray booth, recycled air from the scrubber is reused and fed back to the booth. The scrubber is implemented to remove the toxic gas and paint particles from the pass-through air by using chemical solutions of reagents or using dry absorbent. The scrubbers using chemical solutions are termed *wet*, and those with dry absorbent are termed *dry* [17]. Air through the dry scrubber is relatively stable in humidity, and recycled air from the wet scrubbers absorbs moisture from the chemical solutions and increases the amount of vapor in the air, thereby raising the humidity. The dry scrubber-equipped booth is the study subject of this research.

A typical air flow route for the paint shop booth is shown in Fig. 12.

Fresh inlet air will be first treated in the paint shop building supply unit (as air supply unit I in Fig. 12) to the building set point temperature. This will maintain a comfortable working environment for the worker and to protect the weather-sensitive equipment. Then, the building air will be reused in the booth air supply unit (as air supply unit II in Fig. 12). Finally, the booth air will be recycled in air supply unit III as shown in Fig. 12. Both temperature and humidity need to be controlled in the painting booth to guarantee the quality of paint. The studied case uses a feedforward system. Booth temperature and humidity are controlled through the air released from the top of the booth roof. Regardless of the production rate—speed of vehicles inlet into the booth, the flow rate of the blow air, and its humidity and temperature are controlled to be constant. At steady state, the booth condition is equivalent to the inlet air. Thus, by controlling the air inlet into the booth, the booth condition is controlled.

Several devices and energy forms were involved in this process. The main devices include air fans, heat exchanger, chiller, and dehumidifier. The fans use electricity which is assumed to be constant due to constant rate of air flow. Heat exchanger, chiller, and dehumidifier are the three main devices need to be modeled. The main energy forms are the thermal energy of air, hot water, and chilled water. Thus, the thermodynamic models of heating and cooling energy of these equipment are typical single-machine and multimachine level models as described in the organizational framework.

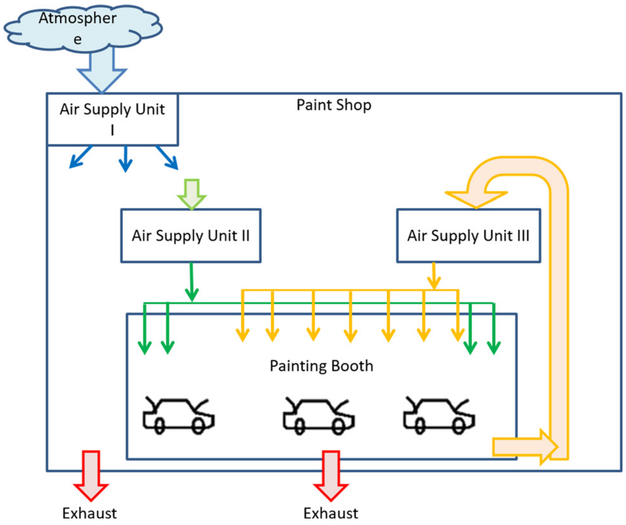

Fig. 12 Painting booth air supply flow sketch

For further analysis on the paint spray booth environment control system, energy models can be established in two aspects: energy supply from hot water and chilled water, and energy demand from the air status change (Fig. 13). Energy demand in the air temperature and humidity change between the inlet and outlet is generally known as the *space load*; energy supply in the hot water and chilled water is known as *secondary equipment load* [18].

In this case, the multimachine and machine level models were established, validated, and put into practice. The procedure is summarized in Fig. 14.

In Fig. 14, the square boxes indicate the actions in model establishment, validation, and implementation; the circular columns show where extra knowledge and information inputs are needed. First, establish general models of space loading and secondary equipment loading. Then, to make the model specified to the studied case, extra information, such as the engineering drawings of air supply house and paint spray booth, and their design parameters, is required to specify the model. Third, according to the specified model, meters and sensors to validate the model are listed. Compared with the current metering system on-site, extra meters may or may not be needed. The booth and its air supply house will run under the current production status to give data on the baseline of specified model. First model validation is based on the baseline data. Once the model is validated, sensitivities on the model inputs can be analyzed, and improvement suggestions can be provided. At this stage, the design tolerance of the system, monetary cost, time, and the possible involvement on the production procedures need to be taken into consideration to give further directions on which improvement can be proceeded. Final two steps are to implement the selected improvement and further validate the model.

Sections 4.2.1 to 4.2.3 detail how the models were established, validated, and implemented.

4.2.1 Process Model Establishment.

The energy model was built for both space load energy demand and secondary equipment load supply.

4.2.1.1 Space load energy demand.

In the studied case, building air is the inlet air to the air supply unit (Fig. 13). The building air of plant is controlled on this temperature, but not humidity. The air supply unit needs to adjust the inlet air to its designed

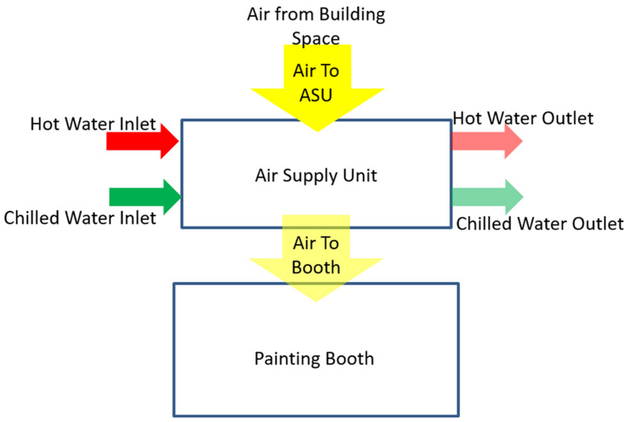

Fig. 13 Energy supply and demand models

temperature and humidity through heat exchange with hot water and chilled water.

The flow chart of the model can be found in Fig. 15.

The air from the building will be used as the inlet air of air supply unit II, and the sensors in the unit will measure the temperature and relative humidity of the inlet air. Inlet air temperature and humidity are not always exactly the same as the plant. For example, when the air inlet location is on the penthouse of the plant building, the outdoor environment temperature could cause the air temperature to drop or increase depending on the thermal conductivity of the building shell and temperature difference between the building air and outdoor environment. Another more common example is the heat from the fans. Fans use the electricity to blow the air from building to air supply unit. During this process, the air will go through the high-speed fans and gain heat from the fans. Generally, the air temperature will increase 2 °F per fan. The measured temperature and humidity will be used to compare with target parameter. Controllers will tell the system, if the air need to be dehumidified, heated, or cooled. Directly heating and cooling process is straightforward. The air goes through the heat exchanger (hot water heat exchanger for heating or chilled water heat exchanger for cooling) to reach the target temperature. Humidity is controlled through a wet wall or nozzles to increase water content. The dehumidification process is more complex. Desiccant is widely available in the market, but it is expensive and it is not feasible to use it in a system with restricted humidity control which requires constant replacement. The studied case uses a cooling process for dehumidification. Before discussing the detail dehumidification process, there are several concepts that need to be clarified.

Generally, the air has two parts: dry air and vapor in the air. Dehumidification process decreases the amount of vapor in certain amount of dry air, i.e., decreases the *absolute humidity* through condensation. *Absolute humidity* can be represented in kilogram of water in kilogram of dry air. At certain temperature and pressure, the maximum amount of water can be absorbed in the air is called *saturate*, which is defined as 100% *relative humidity*. From here, the *relative humidity* (rH) can be calculated through the ratio of water amount in air (W) to water amount in saturated air (W_s) (as Eq. (2))

$$rH = \frac{W}{W_s} \tag{2}$$

where rH is the relative humidity (%), W is the humidity ratio (kg/kg dry air), and W_s is the saturated humidity ratio (kg/kg dry air).

Constant pressure is assumed throughout the research work. At constant pressure, air with higher temperature can absorb more water. In other words, lower temperature air has lower saturated humidity ratio. The dehumidification process decreases the humidity ratio through a cooling process. When the saturated water ratio at temperature T_2 is smaller than the water ratio at temperature T_1 ($W_{S,T_2} < W_{T_1}$), water will be condensed and removed, and air humidity ratio decreases. This process requires a large amount of cooling energy. On the other hand, temperature T_2 to condense the water from air is usually a very low temperature, much lower than the booth target temperature. Thus, heating energy is required after the dehumidification process.

The energy demand at every process can be calculated through enthalpy (as Eq. (3)) change in two statuses of air—before and after the heat exchanger

$$h = C_{p,a}T + W(C_{p,w}T + h_{w,e}) \tag{3}$$

where h is the enthalpy of moist air (kJ/kg), $C_{p,a}$ is the air specific heat capacity (kJ/kg °C), $C_{p,W}$ is the water specific heat capacity (kJ/kg °C), T is the temperature (°C), and $h_{w,e}$ is the evaporation heat of water (kJ/kg).

The space loading energy is the summation of energy at every process. In the scenario when the air needs to be dehumidified,

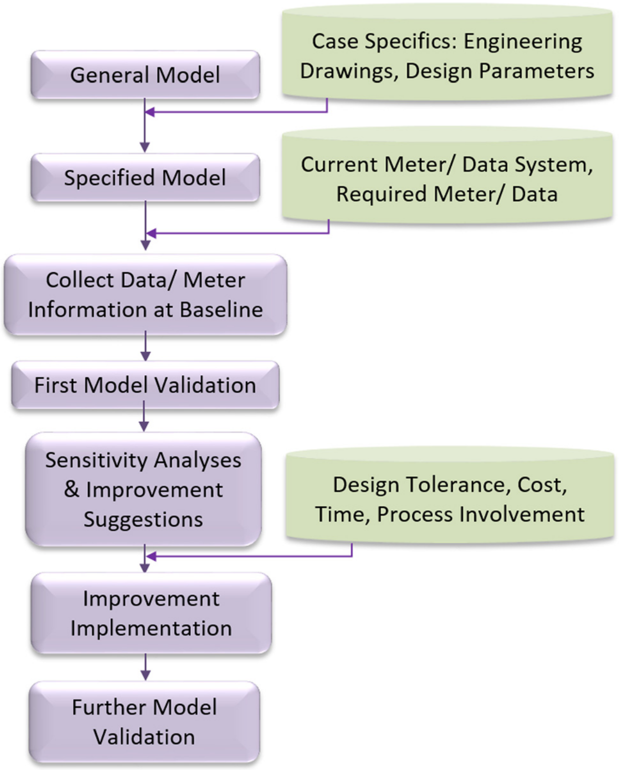

Fig. 14 Action and knowledge input flow chart

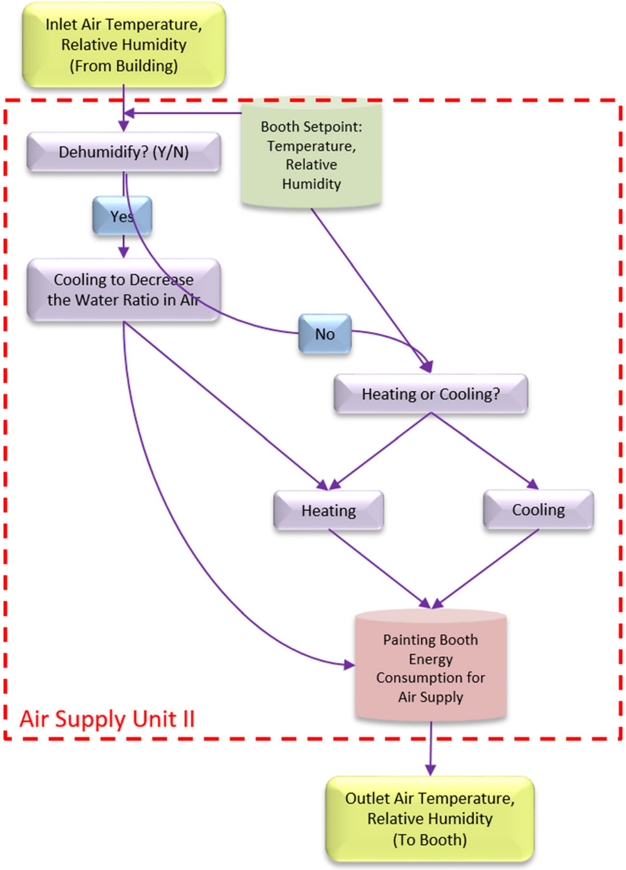

Fig. 15 Air supply energy consumption flow chart

space loading energy demand is the summation of enthalpy change in cooling process and enthalpy change in heating process (Eq. (4)). In a scenario when air only needs heating, space loading energy demand is the enthalpy change before and after the hot water heat exchanger (Eq. (5)). While in a scenario when air only needs cooling, space loading energy demand is the enthalpy difference before and after the chilled water heat exchanger (Eq. (6))

$$E_{\text{dehum}} = \Delta h_{\text{overchill}} + \Delta h_{\text{reheat}} \tag{4}$$

$$E_{\text{heat}} = \Delta h_{\text{heat}} \tag{5}$$

$$E_{\text{cool}} = \Delta h_{\text{cool}} \tag{6}$$

where E_{dehum} is the space loading energy demand at dehumidification scenario (kJ/kg), $\Delta h_{\text{ovechill}}$ is the enthalpy change of moist air in dehumidification process (kJ/kg), Δh_{reheat} is the enthalpy change of moist air after dehumidification heating process (kJ/kg), E_{heat} is the space loading energy demand at heating scenario (kJ/kg), Δh_{heat} is the enthalpy change of moist air in heating process (kJ/kg), E_{cool} is the space loading energy demand at cooling scenario (kJ/kg), and Δh_{cool} is the enthalpy change of moist air in cooling process (kJ/kg).

The overall energy during a certain period of time can be calculated through the flow rate and integration over time (Eq. (7))

$$E_{\text{space}} = \int E(t)\cdot Q(t)dt \tag{7}$$

where E_{space} is the space loading energy demand at certain period of time (kJ), $E(t)$ is the space loading energy demand at certain point of time (kJ/kg), $Q(t)$ is the air flow rate at certain point of time (kg/s), and t is the time.

4.2.1.2 Secondary equipment load supply. The energy of space loading is provided through the secondary equipment—heat exchangers in this case.

In a closed recirculating system, hot water goes through the heat exchanger and uses the temperature between the water and air to heat the cold inlet air. By controlling the flow rate of the hot water, air can be heated to different temperatures. A simplified heat exchanger sketch is shown in Fig. 16. The energy of secondary equipment load energy supply can be calculated as Eq. (8). So is the chilled water for cooling process

$$E_w = \dot{m}\cdot C_w\cdot \Delta T \tag{8}$$

where E_w is the secondary equipment load energy (kJ/s), $\dot{m}$ is the hot water or chilled water flow rate (kg/s), C_w is the water heat capacity (kJ/kg K), and ΔT is the water temperature difference between inlet and outlet (K).

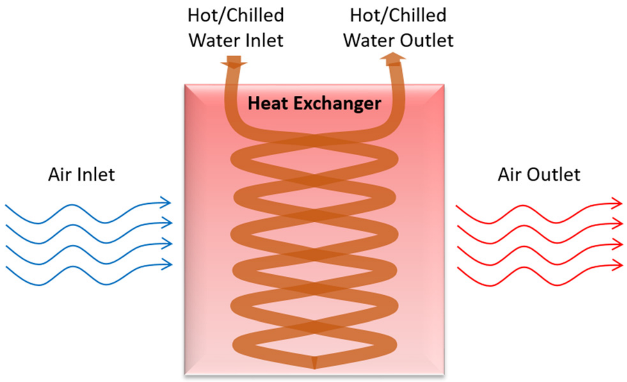

Fig. 16 Heat exchanger sketch

Generally, the water heat capacity is constant at standard condition ($T = 25\,^\circ\text{C}$ and $p = 101\,\text{kPa}$), but when the water temperature variation is large, the variation of C_w cannot be ignored. C_w can be calculated through fitted model (Fig. 17) in certain temperature range ($C_w = f(T)$).

Thus, in a certain period of time, the energy can be calculated as follows:

$$E_w = \int m(t)\cdot C_w(T)dTdt \tag{9}$$

In this equation, the water flow rate is written as a function of time ($m(t)$), and water heat capacity is written as a function of temperature ($C_w(T)$). Both heating and cooling processes can be calculated as Eq. (9), but the polynomial fitting at different temperature could result in different functions. Thus, the function of water heat capacity should be modeled differently according to the temperature range variation.

4.2.2 Model Validation. Inputs and outputs of the models are summarized in Fig. 18.

Every input of the 12 ones listed in Fig. 18 needs to be specified for the studied case.

Inputs 1, 2, 4, 5, 7, 8, 9, and 10 are monitored through the meter and data system. Input 3 is determined through the designed parameter on engineering drawings. Inputs 6, 11, and 12 are not monitored. Flow rate meters for water are installed for model validation purpose. Avoiding the interference with the production activities, clamp-on meters were selected. However, the quantification of dehumidification chilling temperature is complex.

Figure 16 is a simplified sketch of heat exchanger. In this case of dehumidification, water cooling coil is used. In a typical water cooling coil, chilled water went inside of the header and cool the air going through the coil. When the warm humid air reaches the chilled coil and the fins around it, heat is exchanged between them. The air was chilled, and humid will condense out and form water drops on the surface of fins. When the weight of the drop is heavy enough, it falls into the drain pan at the bottom of coil.

In a cooling coil, there are many rows of coils. According to the different locations of the coils, the surface temperatures of the coil are different. Therefore, the amount of water condensed from each row of coils is different. Mansour and Hassab [19] discussed how the design of cooling coils can affect the dehumidification process, and how the temperature of the dehumidification can be simulated based on the different designs of the coils. Unfortunately, the design parameters of the dehumidification cooling coils in our studied case are not available for further simulation of this process. Single dehumidification was assumed and estimated through both the space loading and secondary equipment models.

With all the inputs data metered or got from the model and design drawings, certain period of the production day was selected as the test time for baseline to validate the model accuracy.

Figures 19 and 20 show the model outputs from space loading demand and secondary equipment supply of heating and cooling energy. The data given in the two figures are normalized to protect confidentiality of the plant. Before normalizing, the supply energy

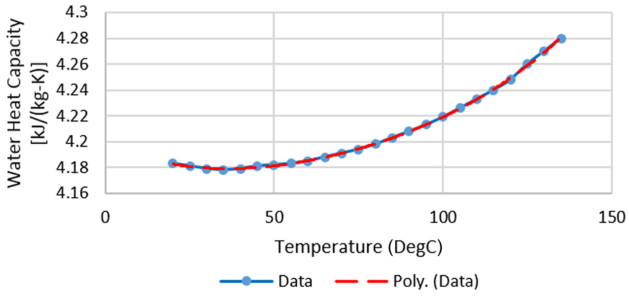

Fig. 17 Water heat capacity and fitted polynomial plot

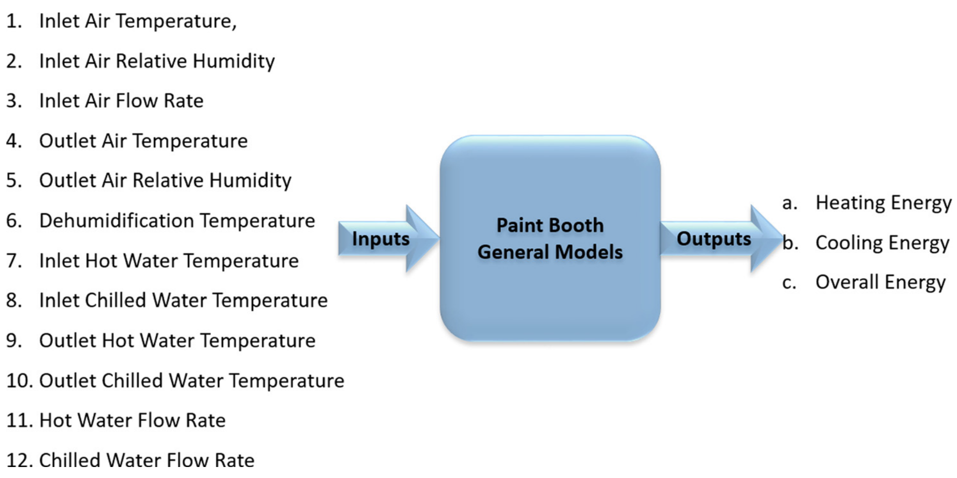

Fig. 18 Model inputs and outputs sketch

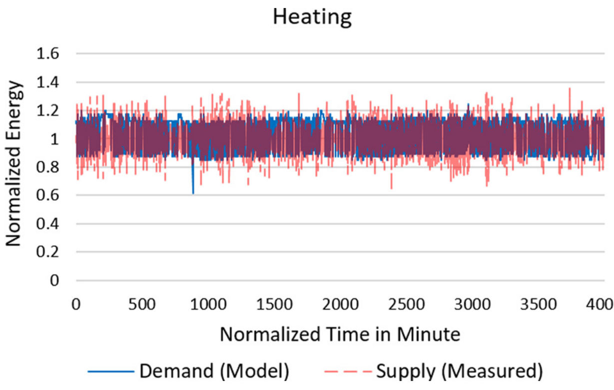

Fig. 19 Baseline heating validation

is a little higher than the demand energy. The solid lines are the supply energy, and the dash lines are the demand energy. The trend of the two lines in each figure follows each other well. This indicates a good accuracy in the models. Further into the inputs of the models, the temperatures of the inlet air are relatively constant comparing with the humidity change, since the indoor only controls the temperature. This explains the big variations in cooling energy, because most of the cooling energy was used on dehumidification process, while the heating energy is used for air heating up after the dehumidification process.

4.2.3 Model Implementation. Based on the model and available techniques, suggestions were made to the studied plant for energy conservation.

Also, during the information exchange with energy and production specialists, it is found that the painting spray booth allows the fluctuation of temperature between 68 and 86 °F. Based on the temperature tolerance range, suggestions on temperature set point change were also given. Further validation on the model and the suggestion was made during the nonproduction days to avoid product quality issues.

The same inputs data are required. During the nonproduction period, the painting spray booth temperature set point was adjusted according to the suggestions.

Figures 21 and 22 show the model outputs of the pilot study on the temperature set point adjustment. During the pilot study, the set point of paint booth was changed. For example, during the normalized time range of 0–88, the booth temperature was changed from 72 (baseline) to be 78 °F; during the time range from 89–170, the set point was controlled to 76.5 °F. Linear optimization can be used to select optimal operation temperature. The approach can be expressed in the following equation:

$$\begin{aligned} &\min E \\ &\text{s.t., } 68 \le T \le 86\,^{\circ}\text{F} \end{aligned} \tag{10}$$

where E is the space energy demand, calculated through Eqs. (2)–(7). The optimal temperature set point can be adjusted in a certain period of time (a year in this case) or frequently according to the design constraints and instant inlet air condition.

It is noticeable during the pilot study that the supply energy has a delay, and it takes some time to be stable. Also, there are several overshoot and data fluctuation. Otherwise, the two models align with each other and can be used for suggestions on energy conservation. It is worthy to pay attention that the minimum energy consumption time is from 650 to 1010. During this period of time, the

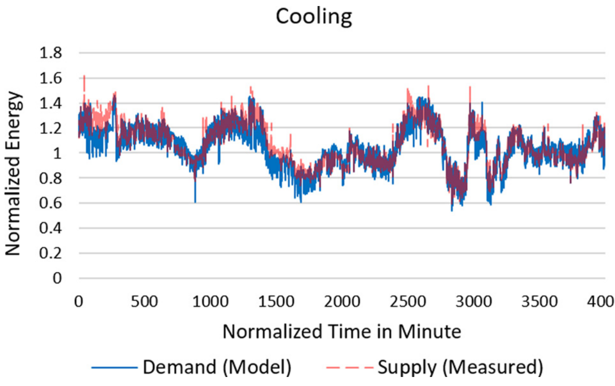

Fig. 20 Baseline cooling validation

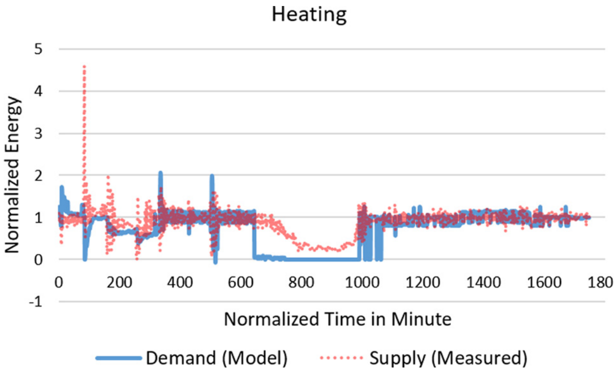

Fig. 21 Temperature set point adjustment study (heating)

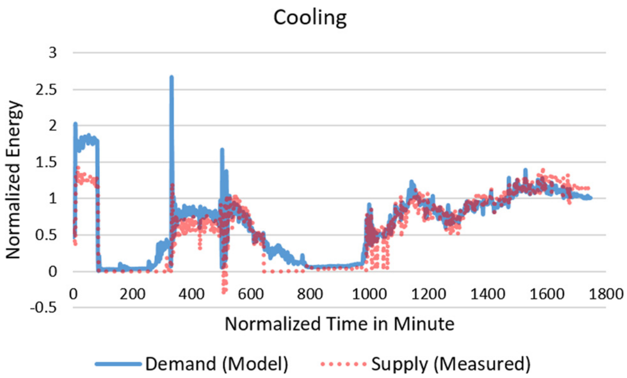

Fig. 22 Temperature set point adjustment study (cooling)

weather is very dry, which leads to low humidity in the building, also the inlet air to the air supply unit of painting booth. Due to the low humidity of inlet air, there is no need for dehumidification process and reheating up, the only energy is used to control the temperature of the air.

It is proved that the local weather and booth set point booth will affect the energy consumption tremendously. Final suggestions were given to the plant. According to the ability of the control system, single optimal set point and real-time set point based on the historical weather information can be chosen.

After the pilot study, the models can be used offline to predict the least energy consumption set points for the painting booth. Annual energy conservation is estimated to be range from the approximately 30% (hourly variable set points adjustment) to 80% (annual variable set points adjustment). According to the model suggestions, the adjustment can be made during the production time slowly to achieve the final goal of energy saving.

Though the model was built on the postprocess phase in the temporal framework, the whole energy model establishment, validation, and implementation reviewed the process design and went through the process adjustment phase.

5 Contribution and Conclusion

In this paper, manufacturing system temporal and organizational framework was introduced to guide the understanding on various levels and systematic energy model. Through the literature review of the works done in this area, the automotive manufacturing processes were introduced. A systematic modeling approach was proposed and used in a case study from a typical automotive assembly plant to illustrate how the approach can be applied. Compared with other available models, the proposed approach takes the consideration of current plant metering status and shares the information among levels of models. The proposed approach can efficiently identify the energy critical components in the plant and provide valuable improvement suggestions.

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