Analysing the use of waste factory heat through exergy analysis

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Abstract

When analysing the energy efficiency of a factory, it is useful to consider the whole system including both the manufacturing processes and the factory building. The latter is included due to its significant energy usage associated with production. The depletion of natural resources can be linked to the consumption of stocks of non-renewable exergy, and an analysis of this can be used to quantify the impact on natural resource consumption. This paper presents a case study into the use of waste heat from a factory building to supplement the heating system.

An engine machining line within an automotive factory is analysed, using a simulation based approach in which the factory heating system is compared with and without heat reuse. The results quantify and compare the changes in efficiency and resource use based on both energy analysis and exergy analysis; effectively quantifying natural resource consumption due to changes in the manufacturing system.

Introduction

MOTIVATION

In view of sustainable development, the conservation of natural resources is a cardinal objective that must be addressed. Therefore as processes and systems operate, the quantification of natural resources consumption becomes an issue of significant importance. Thermodynamics offers a scientifically sound basis upon which such an analysis could be carried out. Such studies may use either the 1st or 2nd law of thermodynamics. The former however has inherent limitations which makes its use difficult for this purpose. Chiefly due to the fact that energy is a conserved quantity, therefore quantifying resource consumption through a conserved quantity becomes an issue. As resources are being consumed, they undergo transformations which involve changes in the quality of the resource flow. This aspect of energy quality is not captured by the 1st law thus making its use less suitable in the mentioned context.

(Szargut et al., 2002) suggests that the quantity exergy, based on the 2nd law can be accepted as a common measure for the quality of natural resources and that the cumulative consumption of non-renewable exergy is a measure of depletion of non-renewable natural resources. He further proposed the term, ecological cost using this concept and provides exemplary calculations of a blast furnace process. When analysing the resource efficiency of a system, it is imperative to differentiate between the terms resource usage and resource consumption. While tools such as life cycle analysis (LCA), material flow analysis (MFA), and substance flow analysis (SFA) are useful tools, they do not adequately address the question of resource consumption. (Gößling-Reisemann, 2008) details the shortcomings of such approaches and argues that resource consumption is better quantified through quantities based on the 2nd law of thermodynamics. (Rosen, 2009) Reviews the existing exergy based techniques for the assessment of the environment and ecology. He further argues that such analogous relations between energy, ecology and the environment may not always be useful and sometimes even misleading. (Wall, 2005) considers the earth to possess exergy capital which should be conserved to meet the goal of a sustainable future. He further concludes that exergy is a stronger concept than energy for the description of natural resources consumption. (Valero, 2006) advocates the use of exergy accounting for a clear understanding of natural resource degradation and outlines the drawbacks associated with such an approach. (Connelly and Koshland, 2001) present the concept of an ecosystem evolution analogy for industrial systems. Further it is stressed that natural resource depletion can be considered the exergy removal from the non-renewable resource, thereby making exergy destruction an important parameter along with others that could possibly address the objective of environmental benefit. Therefore, it is an objective of this paper to quantify the change in exergy destruction as the system under study is altered. This will allow the application of the various methodologies present in literature to assess resource consumption as the system is altered for improved resource efficiency.

With factories in general, a considerable proportion of energy is used to maintain the building environment suitable for its processes and occupants. The technical building services (TBS) task is to provide these facilities along with compressed air, water, steam and other resources that are required by the processes. A study at the European Union level (Herrmann and Thiede, 2009) shows the average energy usage by the technical building services in the industry was 35 %–40 % of the total industrial energy use. It is understandable therefore to address the TBS as part of the manufacturing system. In the current study, the automotive factory faces a similar situation where the building HVAC system accounts for roughly the same energy usage as of the production equipment.

EXERGY ANALYSIS OF BUILDINGS

Buildings have been analyzed for their energy efficiency widely because of their high energy demand. In somewhat recent literature, buildings have been analyzed on an exergy based approach using the so called "LowEx" methodology where the energy quality of supply and demand streams is sought to be matched (Hepbasli, 2012, Schmidt, 2004, Shukuya and Hammache, 2002); Figure 1 depicts this required matching. The effect of this is reduced exergy destruction while increasing efficiency. Based on this concept, it can be argued that exergy management of buildings offer greater if not equal potential to natural resource savings in buildings as compared to an energy based approach.

The low exergy supply streams can be composed of sustainable flows where two examples of such technologies are solar water heaters and heat pumps. A review by (Hepbasli, 2012) describes these LowEx technologies that have been applied in various research studies in more detail. Below, the general approach for calculating the exergy efficiency of a building is briefly given. The detailed background for designing low exergy buildings can be found in (Schmidt, 2004). Using the LowEx approach, the building efficiency can be analyzed based on dividing the flow of energy from the primary source to the building envelope into seven stages or modules. The schematic from

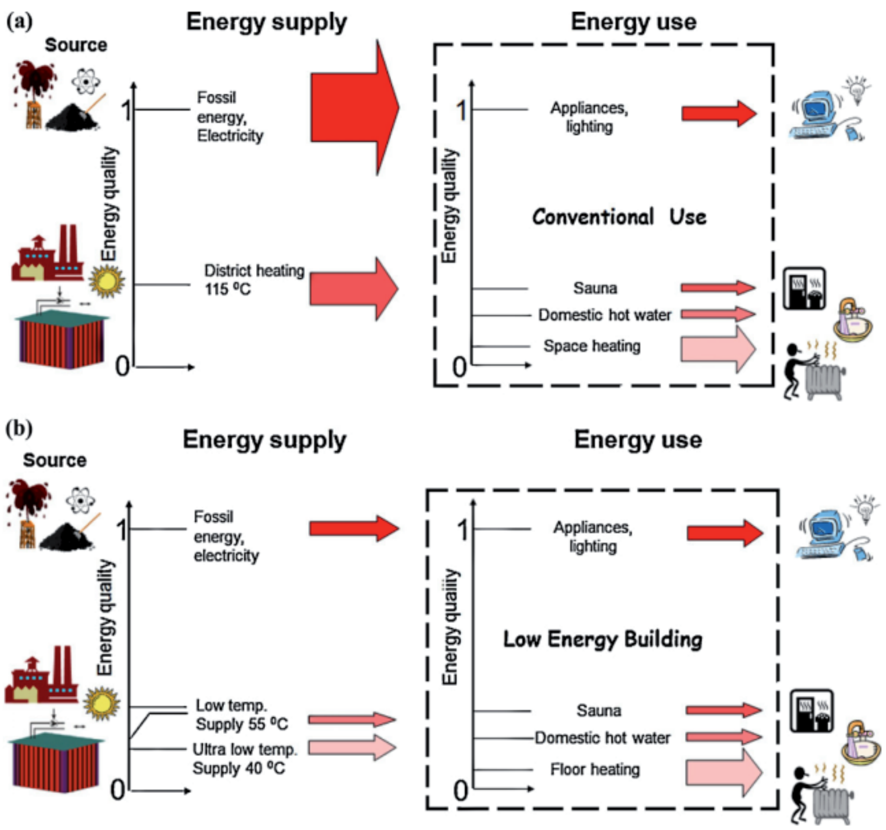

Figure 1. Energy quality schematic: (a) conventional use, (b) low energy building with supply and demand quality matching. Source: Hepbasli, 2012.

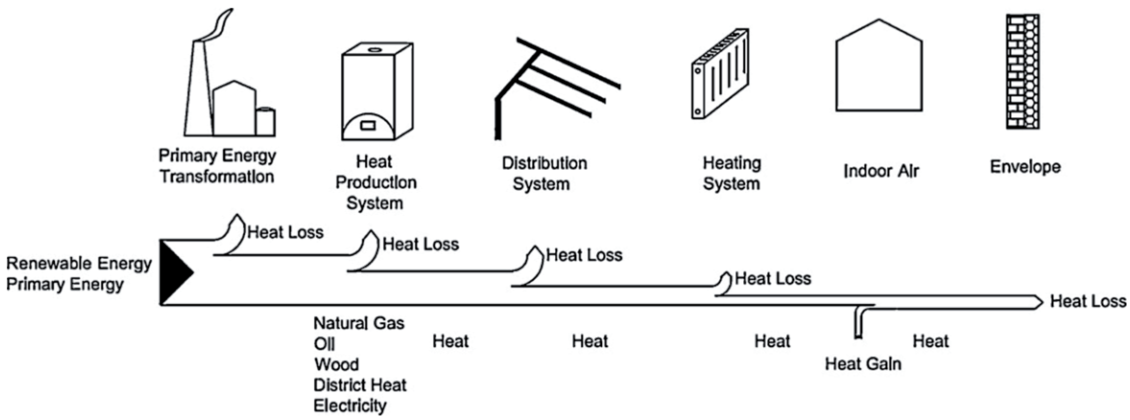

Figure 2. Energy utilization in building services equipment (Hepbasli, 2012).

(Hepbasli, 2012) in Figure 2 shows the modules for the energy flow of the building services energy utilization scheme.

Through this approach, a detailed analysis can be carried out starting from the primary energy transformation, going through the various stages of change and delivery before reaching the building envelope and finally dissipating into the atmosphere. The energy/exergy demand is calculated backwards from the envelope up to the primary energy transformation stage. This allows detailed quantification of natural resource consumption based on the building demand. In order for this approach to be analyzed for the current case study, the exergy of the involved flows need to be calculated.

Exergy was defined by (Szargut et al., 1988) as "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes". A detail about exergy basics and various types and its use for manufacturing will not be given here, but can be found in literature texts such as (Bejan, 1988, Dincer and Rosen, 2012, Brown et al., 2012, Sciubba and Wall, 2010). The exergy of the three types of flows involved in the present study are then calculated as follows.

Electrical energy is pure work, and therefore equal to exergy:

$$\dot{E}_{electrical} = \dot{Ex}_{elec}$$

Considering air to be an ideal gas, the exergy flow in the system in the form of hot air mass flow is given as:

$$\dot{Ex}_{air} = \dot{m}_{air} c_{air} \left[(T_{in} - T_0) - T_0 ln \left(\frac{T_{in}}{T_0} \right) \right]$$

Where $\dot{m}_{air}$ the mass flow rate of the air; c_{air} is the specific heat capacity of the air. T_{in} and T_0 are air and outside temperatures respectively.

Considering water to be an incompressible fluid, the exergy of hot water flow is calculated as:

$$\dot{Ex}_{wa} = \dot{m}_{wa} c_{wa} \left[(T_{in} - T_0) - T_0 ln \left(\frac{T_{in}}{T_0} \right) \right]$$

Where $\dot{m}_{wa}$ and c_{wa} are the mass flow rate c_{wa} specific heat capacity of the water respectively. These three exergy calculations are sufficient to analyse all flows in the present study.

Application of methodology to factory

The part of the automotive factory under study houses an engine cylinder head manufacturing line. The manufacturing line is composed of a number of steps which can be classified as machining and washing steps. The building heating system uses the waste heat from the machinery and building space within the factory itself to preheat incoming fresh air for higher performance. In summer, the preheat system is disabled to avoid overheating of the building.

The LowEx approach previously described is modified to suit the automotive factory case. Considering the scope of the work and availability of the data, the stages before heat emission and control stage are not considered. Figure 3 depicts the stages of energy and exergy flow that are to be analysed. The primary energy transformation, storage and distribution modules are not analysed in the current study. Therefore, only the effect of using the waste heat from within the building on the heat emission and control module is quantified.

Through this approach, it is possible to compare various cases to assess the performance of the factory's heating system. In this paper, two cases are compared, the description of which follows next.

CASES COMPARISON

For the system analysis, the control volumes outlined in Figure 3 needs to be analysed. The base case represents the actual situation in the factory in which the building heat is reused whereas the alternate case disables the heat reuse. In both the scenarios, the building envelope and room air subsystems remain the same however the heat emission and control system is altered. The exergy calculation in both the cases is dependent upon the key parameter; energy demand that is calculated using a software simulation. Therefore, what follows is a description of the simulation approach.

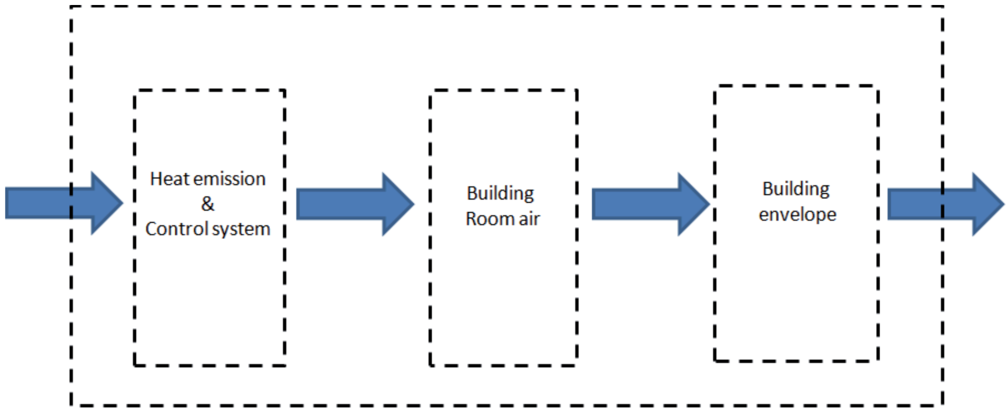

Figure 3. Automotive factory building energy use analysis based on the LowEx approach.

Table 1. Building model construction information.

	Slab-on-ground floor	Flat roof (no ceiling)	External wall	Glazing
U-value [W/m²K]	2.2	0.3	0.4	3.1
Outside layer	Floor insulation	19 mm Asphalt	White-painted steel	6 mm Clear glass
Layer 2	150 mm Concrete	13 mm Fibreboard	100 mm Concrete block	6 mm Air cavity
Layer 3	N/A	100 mm Insulation	100 mm Insulation	6 mm Clear glass
Layer 4	N/A	100 mm Concrete (light)	White-painted steel	

MODELLING AND SIMULATION APPROACH

In the factory, only the overall electrical and heating energy usage was recorded. This necessitated the use of a simulation approach that enables us to analyse subsystems of the factory. The software used for this purpose is EnergyPlus; the reason for its selection being wide acceptance in the academic and consulting fields along with the fact that it is freeware. The energy model of the factory building was created using the Legacy Open Studio (EnergyPlus, 2013) Plug-in and its accuracy depends on the detail of the model inputs. Information on most of the model inputs was gathered through several factory visits and questionnaires to plant managers.

The factory is roughly 100 m long and 56 m wide with the average floor-to-ceiling height of 9.05 m. Double-glazed units are installed on west, south and east facades and cover approximately 54.6 m^2, 47.2 m^2 and 39.8 m^2 of wall area respectively. The external wall is made of two metal cladding layers (outer and inner), 100 mm insulation layer and a 100 mm concrete block layer. Construction data about ground floor and roof have been selected according to the typical construction practice for the particular building age (early 1980's). Table 1 shows the U-values of the most important building construction elements as well as the composition of these elements.

Information about artificial lighting was acquired from the plant manager amounting to a total of 72.5 kW which is on approximately 19.2 hours per day. The production lines electricity consumption profile has been derived from the measured actual electricity consumption which was then used to determine the internal gains from production equipment in the TBS (Technical building services) modelling. Only a minor fraction of this energy is released to the surrounding air as dissipated heat. It has been assumed that only 30 % of energy is dissipated to the surrounding space while the rest of the heat is removed by other measures in the factory. In addition to the model of a building itself, there is a need to create an EnergyPlus model of a Heating, Ventilating and Air-conditioning (HVAC) system. The simplified scheme of the installed HVAC system is presented in Figure 4 which can be divided in two major subsystems:

- The dedicated outdoor air system (DOAS).
- A range of unit heaters (UH).

The DOAS is composed of an air handling unit (AHU) with supply and return fans, main heating coils (HC), heat recovery unit subsystem (HRU) and an air distribution network. The system operates with 100 % outdoor air. The air is distributed to the factory via 32 supply columns where each column delivers around 1,060 l/s of a fresh air. In total 122,000 m^3/h of fresh air is delivered to the factory. The main heating coils are controlled by the supply air temperature sensor which is set to a constant temperature of 17 °C. The heat recovery effectiveness was realistically set to 75 %. Additionally, the UH subsystem is composed of 15 unit heaters, each having a heating coil and a fan. A UH fan re-circulates room air and is switched off when there are no heating requirements. The UH Heating coil is controlled by a thermostat set to 21 °C during occupied period. The set point during unoccupied period (setback temperature) was unknown and was used as a variable in the simulation model calibration process. The temperature profile for the hot water circuit, which delivers hot water from a heat source to heating coils (both in UH and AHU) was created using site data. Finally, the local weather file was used to conduct the simulation. For the model calibration process, two model input variables have been chosen. The first variable used for model calibration is the setback temperature set point and the second is the air infiltration rate. The calibration was setup in jEPlus (jEPlus, 2013), a Java based EnergyPlus shell suitable to manage and run large and complex parametric simulations. For the model validation, the actual heating demand was compared to the measured heating demand for the month of January (Figure 5). It can be seen that the simulated and measured energy requirements for the factory agree to a satisfactory level. This simulation was then used in calculating the heat demand for the two cases to be compared.

BUILDING ANALYSIS

Figure 6 depicts the control volume of the factory building. It combines the building envelope as well as the room air nodes for a simplified analysis.

Applying the steady state exergy balance to Figure 6 yields:

$$\dot{Ex}_{in,air\_DOAS} + \dot{Ex}_{in,air\_UH} + \dot{Ex}_{elec} + \dot{Ex}_{rad}$$

$$= \dot{Ex}_{exhaust\_air} + \dot{Ex}_{heat\ loss} + \dot{Ex}_{dest}$$

It is important to mention over here that the combined outflow exergy is actually the exergy demand to be supplied by the heat emission and control system. This simplifies the exergy balance as follows:

$$\dot{Ex}_{in,air\_DOAS} + \dot{Ex}_{in,air\_UH} + \dot{Ex}_{elec} + \dot{Ex}_{rad}$$

$$= \dot{Ex}_{demand} + \dot{Ex}_{dest}$$

The exergy efficiency of the factory room air and building envelope is therefore:

$$\psi = \frac{\dot{Ex}_{demand}}{\dot{Ex}_{in}}$$

The first key parameter required for calculation of the above efficiency is the energy demand of the factory. The energy demand has been calculated using EnergyPlus using a simulation based approach as detailed previously. The quantity $\dot{Ex}_{in}$ is the exergy supplied from the heating system to factory building.

Since, all the energy supplied by the heating system is used up by the building; there are no energy losses in this process. The energy efficiency of the room and building envelope part

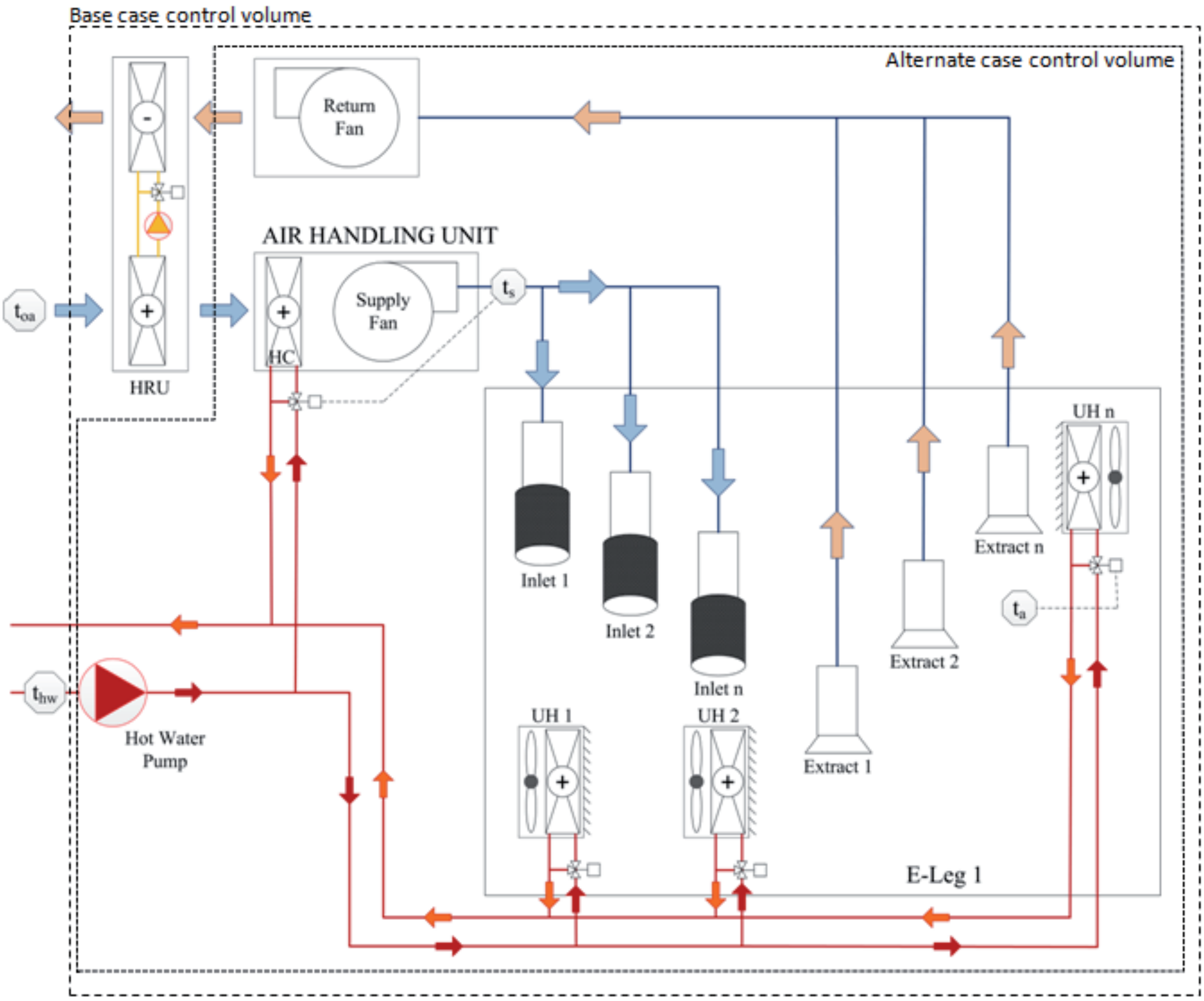

Figure 4. Detailed drawing of the factory HVAC system.

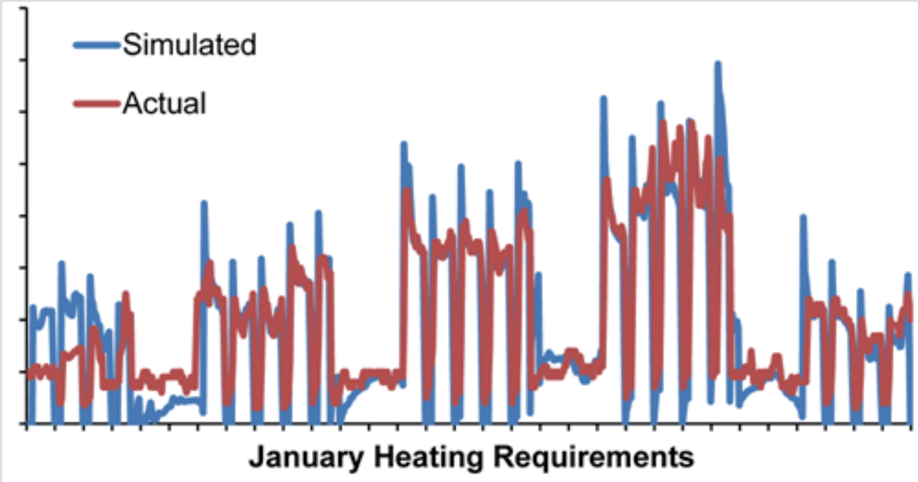

Figure 5. Actual Vs. Simulated Energy requirements.

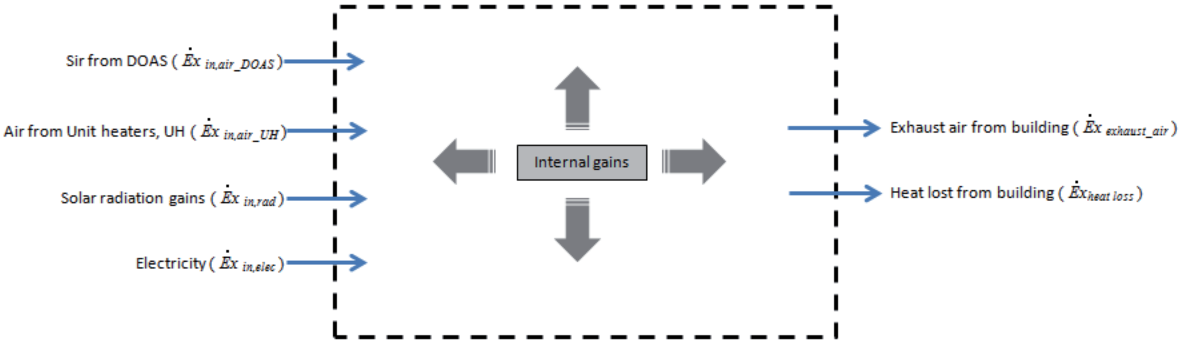

Figure 6. Factory building control volume.

is always 100 % and therefore this metric has no use for the analysis of this stage.

Following on from this, the exergy demand is as follows:

$$\dot{Ex}_{demand} = F_q \cdot \dot{Q}_h$$

$$F_q = 1 - \frac{T_0}{T_r}$$

Where $\dot{Q}_h$ is the heat demand of the factory building, F_q is the quality factor, T_0 is the outside temperature and T_r is the building space set point temperature. These parameters allow us to study the building and room air efficiency for the factory.

BASE CASE HEATING SYSTEM ANALYSIS

The heat emission system control volume is depicted in Figure 7. It is composed of two main components, the dedicated air handling system (DOAS) and the Unit heaters (UH) corresponding to Figure 4.

Considering the air inflow to the system is fresh air supply from the ambient, it has zero exergy. Flows such as electricity and hot water feed are comprised of more than one streams that are similar. They can be represented by singular terms that are summations of the separate similar flows. The exhaust air physically does not enter the system, but the energy/exergy is extracted from it that enters the system, therefore Figure 7 depicts it as such. The exergy balance is then given as follows:

$$\dot{Ex}_{in,exhuast} + \dot{Ex}_{in,wa} + \dot{Ex}_{elec}$$

$$= \dot{Ex}_{out,air} + \dot{Ex}_{out,exhaust} + \dot{Ex}_{out,wa} + \dot{Ex}_{dest}$$

Combining the water and exhaust air for the in/out flow terms, the exergy balance can be written as:

$$\Delta\dot{Ex}_{wa} + \Delta\dot{Ex}_{exhaust} + \dot{Ex}_{elec} = \dot{Ex}_{out,air} + \dot{Ex}_{dest}$$

The exergy delivered to the system is therefore the summation of the first three terms in the above equation. The exergy efficiency is then given as:

$$\psi = \frac{\dot{Ex}_{out,air}}{\Delta\dot{Ex}_{wa} + \Delta\dot{Ex}_{exhaust} + \dot{Ex}_{elec}}$$

Where the electric power consumed is the exergy rate delivered to the fan coil system.

Using the energy balance one can formulate the energy efficiency as:

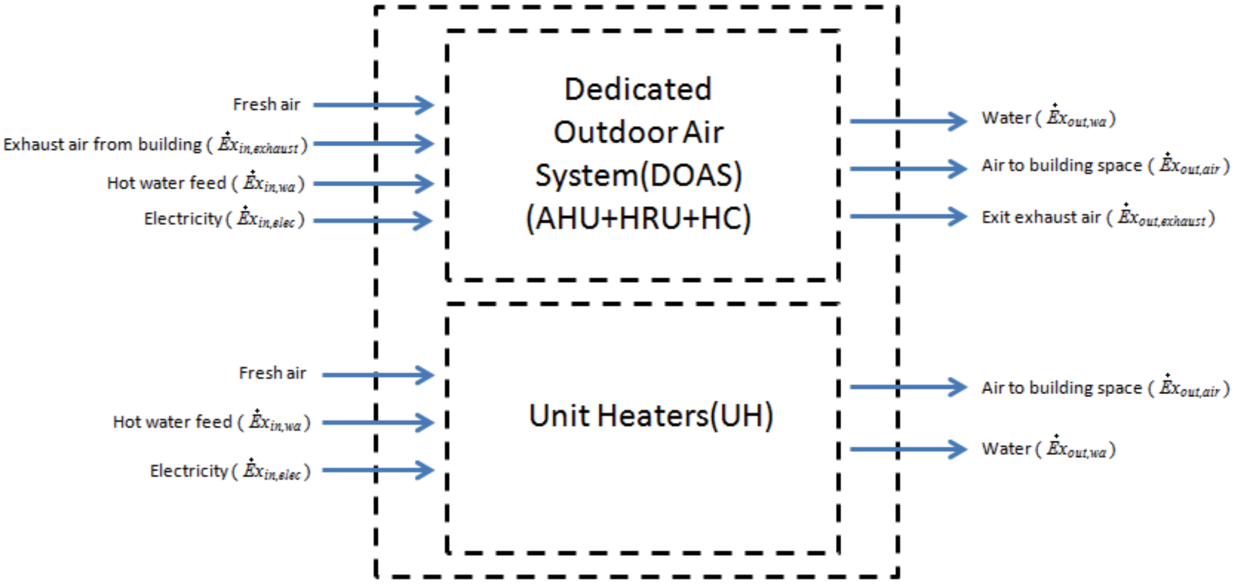

Figure 7. Heating system control volume.

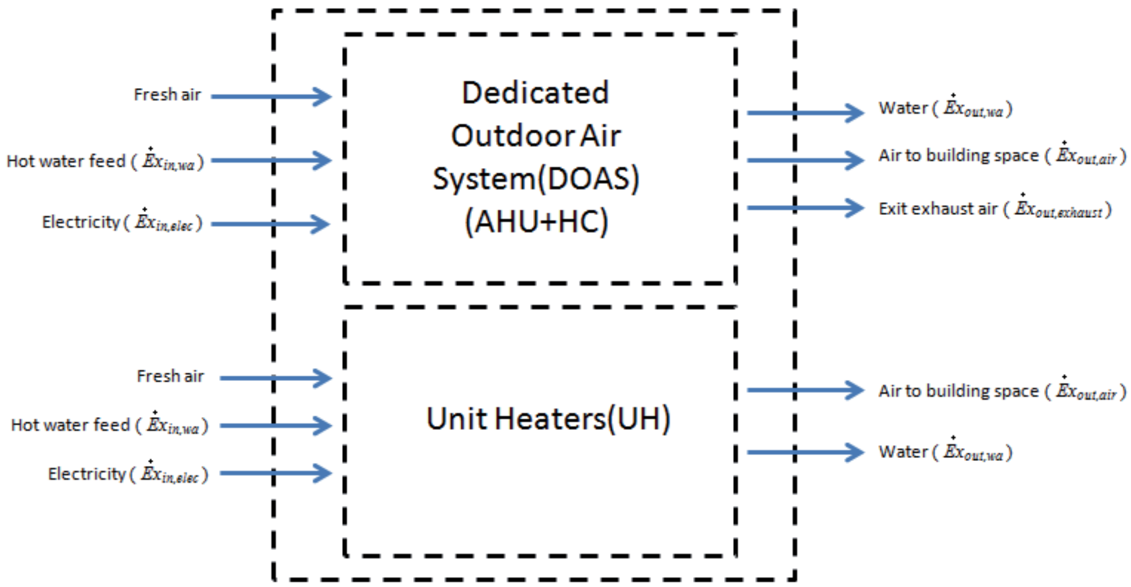

Figure 8. Heating system without heat reuse.

$$\eta = \frac{energy\ in\ product}{energy\ supply} = \frac{\dot{E}_{out,air} - \dot{E}_{fresh\ air}}{\Delta\dot{E}_{wa} + \Delta\dot{E}_{exhaust} + \dot{E}_{elec}}$$

Where η is the energy efficiency and the rest of the terms are the energy carrying steams.

In order to assess the quantity of energy or exergy involved, the net delivered energy or exergy to the heating system can be viewed as the heat demand for the heating system itself which are written as follows:

$$Ex_{heating\ demand} = \Delta\dot{E}x_{wa} + \dot{E}x_{elec}$$

$$E_{heating\ demand} = \Delta\dot{E}_{wa} + \dot{E}_{elec}$$

The exergy destruction within the heating system is calculated from the balance equation. This parameter is of significant importance and can be considered a measure of natural resource consumption.

$$\dot{E}x_{dest} = \Delta\dot{E}x_{wa} + \Delta\dot{E}x_{exhaust} + \dot{E}x_{elec} - \dot{E}x_{out,air}$$

Alternate case heating system analysis

Figure 8 shows the control volume of the heating system without factory heat reuse. This scenario is not the real situation at the factory and is therefore simulated.

Following the same formulation as the previous section, based on the energy and exergy balances, the energy and exergy efficiencies are:

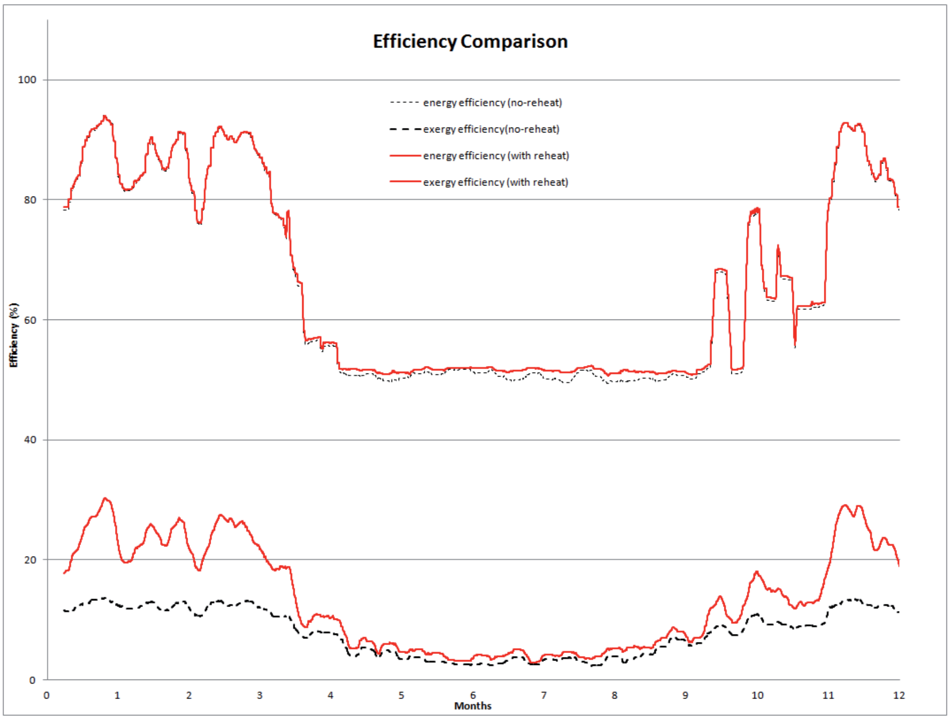

Figure 9. HVAC system efficiency comparison for the two cases.

$$\psi = \frac{\dot{Ex}_{out,air}}{\Delta\dot{Ex}_{wa} + \dot{Ex}_{elec}}$$

$$\eta = \frac{\dot{E}_{out,air} - \dot{E}_{fresh\ air}}{\Delta\dot{E}_{wa} + \dot{E}_{elec}}$$

Similarly, the energy and exergy demand for the heating system itself are:

$$Ex_{demand} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec}$$

$$E_{demand} = \Delta\dot{E}_{wa} + \dot{E}_{elec}$$

The exergy destruction for the heating system is given as:

$$\dot{Ex}_{dest} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec} - \dot{Ex}_{out,air}$$

The efficiencies together with the demands and the exergy destruction allow us to assess the performance of the heating system and compare the two cases.

Results Analysis and Discussion

The results compare the performance of the factory HVAC system for the two cases based on the parameters derived earlier. The analysis uses data for one year and evaluates the energy and exergy balances for the factory in local weather conditions. Figure 9 compares the results calculated with hourly data for one year that have been smoothed for clear interpretation.

The energy and exergy efficiencies of the heating system for the two cases is plotted where the improvement can be seen from the plot. As the gap between the trances is more significant for exergy efficiency, it can be understood that reusing the heat has a larger impact on the exergy efficiency metric. Furthermore, the effect is more visible in the colder months as compared to the summer months when the heating system is active. The average energy efficiencies for the scenarios are found to be 96.13 % and 97.02 %. The average exergy efficiencies for the two cases are found to be 14.04 % and 19.09 %.

In addition to the efficiencies, the magnitudes of energy and exergy involved are equally important. Figure 10 and Figure 11 show the energy and exergy demand of the HVAC system for the two scenarios. The trace of energy demand of the heating system shows a significant decrease due to heat reuse. The total values are found to be 2,962 MWh/year compared to 1,329 MWh/year for the two cases. Similarly a significant reduction in exergy demand can be seen in Figure 11 throughout the year. The total exergy demand for the two cases is found to be 851 MWh/year compared to 627 MWh/year. Finally, Figure 12 shows the exergy destruction in the heating system; the average values are 732 MWh/year ad 581 MWh/year for the two cases.

Table 2 summarizes the results gathered. The exergy efficiency increase is considerably greater; 5.05 % as compared to 0.89 % for energy efficiency. From Figure 9 it can be seen that the effect is especially significant in the colder months. This is due to the fact that in these times, the system operates with fresh air that needs significant exergy to bring it up to the factory set-point temperature. Comparing the energy and exergy demand, the decrease in demand for the more efficient system is 55.13 % and 36.89 % respectively. Finally, the exergy destruction is reduced by 20.6 % when the heat reuse in active. This is an important quantification as it gives us an idea about the impact of heat reuse on the natural resource consumption.

It should be noted here that this exergy destruction calculation has a shortcoming that should be addressed in future

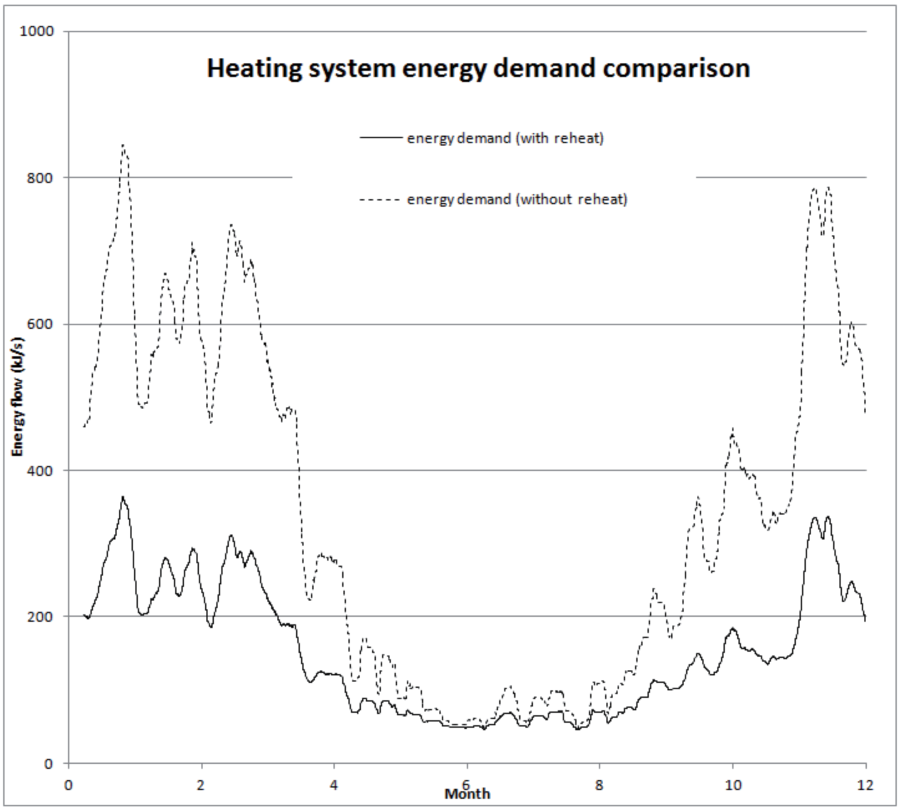

Figure 10. Energy demand comparison.

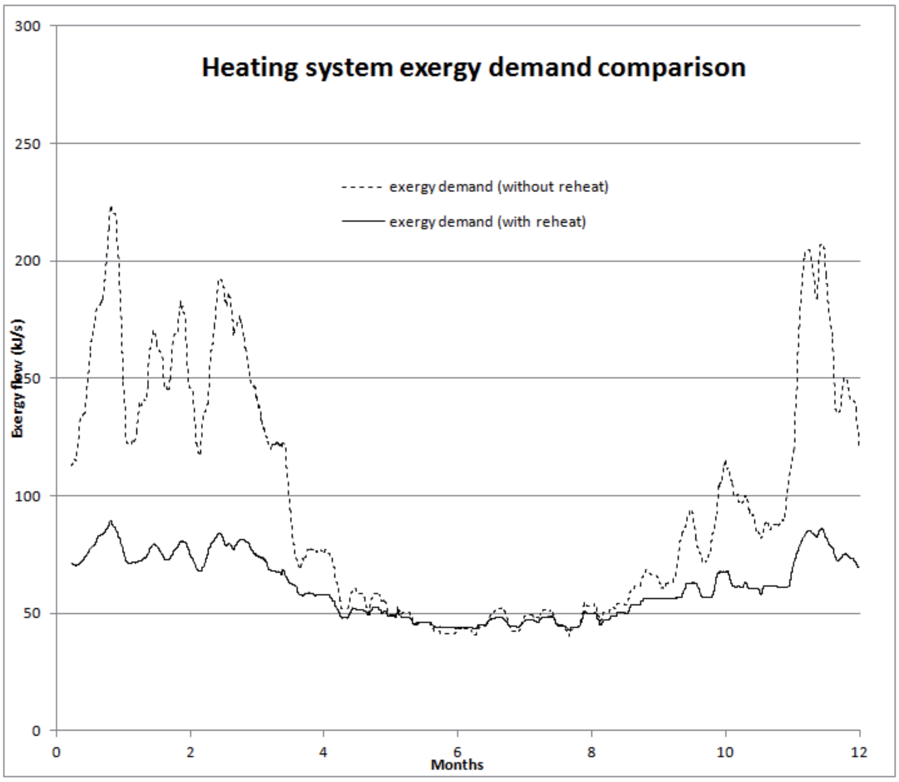

Figure 11. Exergy demand comparison.

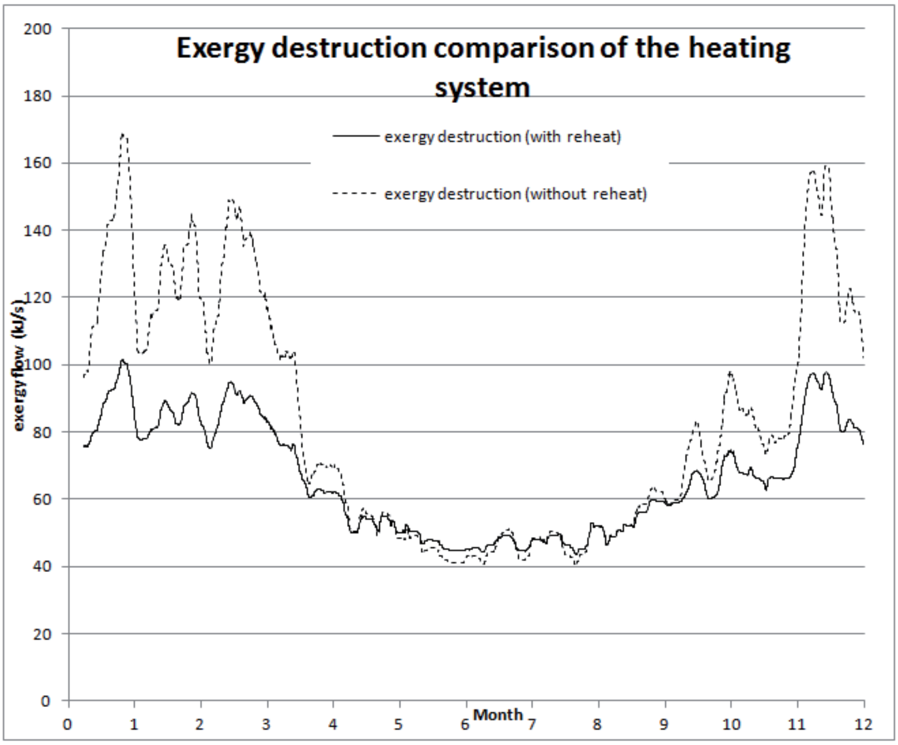

Figure 12. Exergy destruction comparison of the heating system for the two cases.

Table 2. Heat emission system results comparison.

	Yearly Energy efficiency (η)	Yearly Exergy efficiency (ψ)	Energy demand (MWh/year)	Exergy demand (MWh/year)	Exergy destruction (MWh/year)
Case without reheat	96.13 %	14.04 %	2,962	851	732
Case with reheat	97.02 %	19.09 %	1,329	627	581
Improvement	0.89 %	5.05 %	1,633 or 55.13 %	224 or 26.3 %	151 or 20.6 %

work. The exergy destruction calculated in the base case involves the effect of exhaust air on the system; however the heat reuse from the exhaust air cannot be attributed to natural resource consumption by the HVAC system. Additionally, the exhaust air receives exergy due to internal gains which may or may not be from sustainable sources and are not part of the heating system's resource demand. This affects the validity of considering the calculated exergy destruction as a measure of natural resource consumption by the heating system. Therefore, a more elegant methodology is required so as to circumvent these issues and compare varying cases successfully. Perhaps a methodology based on a whole systems approach towards analysing the manufacturing system could provide better results.

Summary

This paper described an exergy based assessment of an automotive cylinder head manufacturing line. The factory building HVAC system performance was analysed based on 1st and 2nd law of thermodynamics. Initially, the method existent in literature for such an analysis is described followed by its modified application to the case study. The energy and exergy based performance metrics were derived and the methodology explained in detail. Two cases were compared to assess the effect of building exhaust air heat reuse on the HVAC system performance. The investigation was conducted using a simulation based approach. The energy and exergy efficiencies and reduction in demand for two cases were calculated. The results suggest that the effect of the heat reuse was significantly more for exergy efficiency with an increase 5.05 % as compared to 0.89 % for energy efficiency. On the other, the energy demand reduction was 55.13 % compared to 26.3 % for exergy demand reduction. Finally, the exergy destruction due to irreversibilities in the heating system was also quantified resulting a saving of 151 MWh/year or 20.6 %. Finally, this method of calculating exergy destruction was discussed and a need for a better technique that incorporates a holistic approach for manufacturing systems analysis was identified. Therefore, this paper presented a methodology applied to a case study in order to quantify the exergy destruction which could be used as a measure for natural resource efficiency of a manufacturing system.

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