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Lifetime Commissioning as a Tool to Achieve Energy-Efficient Solutions

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ABSTRACT

Quality control of the complete energy system is necessary if energy-efficient solutions are to be met. To perform good building operation and quality control of a given system, it is necessary to have information about building systems and assessment tools. The paper presents Norwegian lifetime commissioning (LTC) procedures that are enabling follow-up of the building performance during the building lifetime by establishing a generic framework on building performance data. Further, three developed assessment tools are presented: inspection algorithm for ventilation system, mass balance inspection algorithm for consumer substation, and advanced method for improved measurement of heat pump performance based on data fusion technique. The LTC procedures were tested on two case buildings. The results showed that 20% of all the defined building performances can be monitored by BEMS. Using the mass balance inspection algorithm, it was found that fault in mass balance prevented implantation of desired temperature control for floor heating system. For heat pump performance, measurement of differential water temperature can be very random, hence use of compressor electrical signal can give more precise data on heat pump performance. Comparative analysis showed that detailed monitoring system helps tracking energy use and fault detection in operation. Yearly and hourly profiles of energy consumption with separated use and energy carriers are given in the paper.

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1. INTRODUCTION

Buildings are becoming more complex systems, and building energy management system (BEMS) provides much data about the building systems. Implementation of highly energy-efficient solutions and aiming to the zero energy or emission building will require even more building information and high instrumentation. In nowadays practice, however, we meet many faults and issues in building performance, while our decisions are forced by legislative and cost-benefit induced by energy savings [1]. To overcome these challenges, it is necessary to have a tool that can help to provide quality control on building energy performance, to perform fault detection and diagnosis, and overcome poor functional integration induced by information loss. LTC has been recognized as a tool that can perform these given tasks [2-4]. Further, it was shown that by doing Continuous Commissioning, it was possible to achieve improvement in building operation and reduce energy costs [5]. Therefore, the Norwegian LTC procedures were developed to create a good information system during the entire building lifetime. In this study we have adopted commissioning (Cx) as the process of ensuring that systems are designed, installed, functionally tested and capable of being operated and maintained to perform in conformity with the design intent as defined in ASHRAE Guideline 1–1996 [6]. Actually, in this study, LTC is treated as performance verification. Also, LTC is described as performance verification in the work of Kjellman et al. [7].

Since a building process is typically split into fragments with different participants, information loss appears with performance degradation as a consequence [8]. Further, this information loss induces performance degradation as well. In the construction industry, experience can be re-applied and shared among engineers and participants to enhance construction processes and minimize costs and problem-solving time [9]. For example, in the work of Lee and Akin [10], it was found that there is a 12% potential for maintenance improvement by providing proper information support. Analysis of an information monitoring and diagnosis system showed possibility to reduce yearly energy use by 20% due to proper use of information from sensors and software to indentify control problems and equipment faults [11]. Therefore, the purpose of the Norwegian LTC procedures is to be a knowledge-based tool that can enhance collection of building performance information. In this paper, the presentation of the Norwegian LTC procedures was done by using generic data framework for building energy performance. The entire data framework was developed to enable tracking of building performance data.

Among different technologies to provide energy saving opportunities in buildings, energy analysis and building performance evaluation are also taken into consideration [12]. LTC implies also use of such tools. Availability of BEMS and additional measurements are necessary for proper building performance estimation. Further, integration of these measurements and mathematical methods encourage building performance estimation. For example, heating system performance can be analyzed using BEMS data and sequential quadratic programming [1, 13]. Since measurement data can be corrupted by errors, use of data fusion technique can help to estimate real performance data as shown in [14].

The aim of this paper is to present the results and experience of testing the Norwegian LTC procedures. This paper presents the procedures together with three developed tools for assessment of building energy performance. To perform a good building assessment, data from building design, manufacturer technical guides and monitoring system are integrated. The LTC procedures were tested on two case buildings. Applying the proposed generic data framework on all the building performances, the amount of data found in different phases of the building lifetime was estimated. Several findings discovered using the developed tools in both case studies are presented as well. Finally, energy consumption in both buildings is presented. For one case building, it was possible to separately monitor consumption by use and by energy carriers.

2. METHODS

2.1. Norwegian LTC procedures

The Norwegian LTC procedures were developed based on international commissioning experience and national practical experience. The aim of the procedures is to create a good information system between all the participants during the building lifetime. The focus is on ensuring the owner's project requirements so that the performance quality control is enabled. The method has been reported in [8]. The procedures are a manual and consist of nine parts. As a building's lifetime is proceeding, activities described in a certain document have to be fulfilled. An overview of the consisting documents is given in Table 1, where the documents are classified by their purpose and phase in which the documents are supposed to be used.

Table 1. Norwegian LTC procedures structured into the building lifecycle

According to the Norwegian LTC, commissioning work should be done by a new role named *Cx responsible*. A Cx responsible is responsible to realize the owner's project requirements and to provide a system for realizing building performances through the building lifetime. The Cx responsible should provide the same services as a Cx authority in

ASHRAE Guideline 0-2005 [15] or an ITB responsible person in NS 3935, ITB Integrated technical building installations, Designing, implementation and commissioning [16].

Practically, the necessary information for fulfillment of the LTC procedures can be collected in different ways. In our study, a generic framework on building performance is suggested. This framework describes building performance as a data model [8]. The idea to collect building information as a data model came from NS 3451, Table of building elements [17] and NS 3455, Table for building functions [18]. A building element can be defined by a few performance data as shown in Figure 1. Figure 1 shows an example of a generic framework on building performance. A building element can consist of a few sub-elements, which can be defined by a few functions. A function of a building element is a building performance data. The function numbers of an element depends on which performance data are necessary for performance estimation.

Figure 1. Relationship between building elements and functions

As shown in Figure 1, the building elements should be defined according to NS 3451, while building performances are related to NS 3455. In that way, the documentation of Part 9, Performance description in Table 1, from the LTC procedures, can be established. To follow-up desired functions, it is necessary to define measurement of that function as shown in Figure 1. Therefore, measurement of desired performance data should be defined as soon as an element is involved in a building project. This suggested framework on building performance enables generic definition of performance data and their requirements. In that way, different manipulation of performance data is enabled for different purposes.

2.2. Inspection algorithm for ventilation system

Using the above described procedures and generic algorithm on building performances, it was possible to collect data from design, construction and operation phases. After this data were collected, it was possible to perform diverse inspections on available data. Since the documentation of ventilation system is better than the documentation of the other building systems [8], it was possible to find detailed data on each VAV damper and corresponding air diffuser. To make useful information on all this ventilation system data, inspection algorithms for VAV damper integration, and chosen air diffuser were developed. In Figures 2 and 3, the rule-based algorithms for inspection of VAV damper and diffuser are displayed.

Figure 2. Inspection algorithm for chosen damper

Figure 3 Inspection algorithm for chosen air diffuser

If the desired air volume on a VAV damper, $\dot{V}_{air,pr}$, from the design phase is known, and maximal and minimal air volume on a VAV damper, $\dot{V}_{da,\min}$ and $\dot{V}_{da,\max}$, are known from the manufacturer technical guide, the inspection algorithm shown in Figure 2 can be used to check if all the chosen dampers are correct. Figure 3 shows algorithm for diffuser inspection, where it is possible to detect two types of faults: noise, in the case that the chosen diffuser is smaller than designed; and lack of air, in the case that the chosen diffuser is bigger than designed. In similar way as the algorithm for damper in Figure 2, an algorithm for inspection in balancing phase was developed. This algorithm for inspection in balancing phase integrates data from design and balancing phase.

2.3. Mass balance inspection algorithm

In design and balancing phase of hydronic systems, it is possible to meet a problem that water mass balance is not fulfilled in hydronic system. In this study we deal with the mass balance problem in consumer substation. Since branches in consumer substation influence each other, such problem contributes that desired water flow is not achieved in separate branches. Further, if the water flow is different from desired, a desired temperature control cannot be achieved. Consequently, energy consumption can be very different than the designed one. Use of mass balance equation permits detection of flow measurement errors and evaluation of system performance as shown in the work of Menendez et al. [19]. Menendez et al. suggested a method that integrated measurement uncertainty data and the maximum likelihood least-square estimation to estimate true water flow in the branches.

In our study, after we got data from LTC procedures, it was possible to perform different manipulation on water flow data in the consumer substation. The suggested algorithm consists of three steps: 1. estimating real water flow, 2. estimating error, and 3. defining inspection rules. To explain the algorithm for mass balance inspection, simplified supply side branches in the consumer substation are used as shown in Figure 4.

Figure 4. Simplified supply branch

Mass balance equation for the system with one node in Figure 4 can be written as

$$\sum_{j=1} a_j \cdot \dot{m}_j = 0 \qquad (1)$$

where $\dot{m}$ is mass flow rate and a_j is the entry/exit coefficient to the node I. Coefficient a_j is 1 if flow is entering node I and -1 if flow is exiting the node. Eq. (1) should be fulfilled in each phase, design, construction, and operation under the assumption that there is no leakage in the observed system. Due to poor estimation or faults, it occurs that water flows do not fulfilled Eq. (1). Regardless of faults, the system finds naturally balance. For example, if the value of Eq. (1) is higher than 0, the inlet water flow will be decreased and outlet flows will be increased. The achieved balance represents real water flow. The real water flows were estimated by calibrating the model in Eq. (1) to the data from the LTC procedures. The model calibration was done using optimization method as shown in [1, 13], and the objective function was

$$min \quad 100 \cdot \sum_{i=1} \left(M_i - M_{Di} / M_i \right)^2 \qquad (2)$$

where $M = \left\lfloor \dot{m}_1, \dot{m}_2, \ldots, m_j, .., \dot{m}_n \right\rfloor$ is vector consisting of all the real estimated branch water flows, M_D are water flows in documentations, and $i=1,2,3$ is the number of measurement. In our case, 1 for the data in the design phase, 2 for the contraction phase, and 3 for balancing phase. To solve the optimization problem in Eq. (2), the SQP algorithm was used.

After estimated flow rates were obtained, errors between estimated and flow rates in documents at each building phase were calculated. Finally, mean error, μ, and standard deviation of error, σ, for each measurement were used to define inspection rules for mass balance algorithm. The developed inspection rules were the following:

1. If $\mu \leq$ -10%, the water flow rate at the observed branch is always higher than flow rate in the documents.
2. If $\mu \geq$ 10%, the water flow rate at the observed branch is always lower than flow rate in the documents.
3. If $\sigma \geq$ 10%, the branch is wrongly integrated. This means that data in each phase have been chosen arbitrarily without any correlation with previous phases.

2.4 Improved heat pump performance estimation

Data fusion implies the use of techniques that combine data from multiple sources and gather information in order to achieve inferences, which is more efficient and potentially more accurate than if they were achieved by means of a single source. Successful use of data fusion technique for estimating real chiller load was shown in [14, 20]. Use of LTC procedures provided data on HVAC systems and access to BEMS gave possibility to monitor HVAC system performance data. Data from manufacturer technical guide and BEMS measurement were combined to estimate heat pump performance, compressor power and condenser load. In out study, improved heat pump performance estimation implied fused measurement between direct and indirect measurement of compressor power and condenser load. In that way it was possible to obtain improved estimation of heat pump performance.

The reason to implement fused measurement for heat pump performance estimation came for the fact that temperature measurements easily suffer from noise, outlier, systematic error, and uncertainty as noticed in [14]. An example of water temperature measurement of the supply, RT 40, and return, RT 50, temperatures of the heat pump condenser is shown in Figure 5.

Figure 5. Measurement of the supply/return temperature to condenser

In winter period when the heat pump is used to heat the supply water, temperature RT 40 should be higher than RT 50. But due to mentioned difficulties in the temperature measurement, it is possible that measurements as in Figure 5 are obtained. Consequently, direct measurement of the condenser load based on the temperature difference can be wrong. Therefore, in our study the direct measurement is compared and fused with indirect measurement.

In order to make fused measurement it is necessary to define direct and indirect measurement on the heat pump performance, and in this case they are compressor power and condenser load. The direct model of the compressor power was developed based on literature resources in [21, 22]. The compressor power of the isentropic process can be expressed as:

$$\dot{W}_t = \frac{\gamma}{\gamma - 1} \cdot \dot{V}_S \cdot \left[1 + C - C \left(\frac{p_{dis}}{p_{suc}} \right)^{\frac{1}{\gamma}} \right] \cdot p_{suc} \cdot \left[\left(\frac{p_{dis}}{p_{suc}} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right], \tag{3}$$

and finally, the compressor power can be expressed as:

$$\dot{W}_d = \frac{\dot{W}_t}{\eta} + \dot{W}_{loss}. \tag{4}$$

Using Eqs. (3) and (4) the direct measurement of compressor power is defined. In this case the direct measurement of the compressor power is based on the suction and discharge pressures. In Eqs. (3) and (4) the model parameters, which are theoretical compressor volume $\dot{V}_S$, isentropic coefficient γ, clearance factor C, pressure increase and decrease due to suction and discharge Δp, compressor efficiency η, and compressor loss $\dot{W}_{loss}$, are obtained by calibrating the model to the manufacturer data.

The direct measurement of the condense load was obtained using temperature difference:

$$\dot{Q}_{c,d} = \dot{m}_w \cdot c_{pw} \cdot \left(T_{w,out} - T_{w,in}\right), \tag{5}$$

where data on the water flow were obtained from the design and balancing phase.

The additional data for the heat pump estimation were the heat pump performance from the manufacturer technical guide and electrical compressor signal. The manufacturer of the heat pump provided compressor power, condenser load, and evaporator load based on the evaporation and condensation temperatures. Therefore, based on the manufacturer technical data, it is possible indirectly to estimate: the compressor power and the heat pump condenser load. The indirect model of the compressor power is:

$$\dot{W}_{id} = t \cdot \dot{W}_{FL}\left(T_{out}, T_{w,out}\right) \tag{6}$$

where $\dot{W}_{FL}\left(T_{out}, T_{w,out}\right)$ is the compressor power under the full load, and it is possible to get from manufacturer table. t is partial load of the compressor that can be monitored in BEMS. Electric signal from the compressor gives information which part of the compressor is in use. Consequently, it was possible to obtain the information on the partial load.

Before indirect model of the condenser load is introduced, a non-dimensional relation that is equal to the partial load of the compressor is defined as:

$$t = \frac{N_C}{N_{CFL}} = \frac{\dot{m}_R}{\dot{m}_{RFL}} = \frac{\dot{W}}{\dot{W}_{FL}}. \tag{7}$$

Further, using Eq. (7) and relation for the overall heat transfer coefficient of the condenser given in [23], it is possible to define the overall heat transfer coefficient under partial load as:

$$\frac{UA_c}{UA_{c,FL}} = \left(\frac{\dot{m}_R}{\dot{m}_{RFL}}\right)^m = t^m. \tag{8}$$

Finally, the indirect model of the condenser load can be calculated as:

$$\dot{Q}_{c,id} = \frac{1-\exp(-\frac{UA_{cd,FL}}{\dot{m}_w \cdot c_{pw}} \cdot t^m)}{1-\exp(-\frac{UA_{cd,FL}}{\dot{m}_w \cdot c_{pw}})} \cdot \dot{Q}_{cd,FL}\left(T_{out}, T_{w,out}\right), \tag{9}$$

where $\dot{Q}_{FL}\left(T_{out}, T_{w,out}\right)$ is the condenser load under the full load, and it is possible to get it from manufacturer table.

After the direct and indirect measurements of the heat pump performance were obtained, the fused measurement were obtained using the combined best estimate (CBE) method as showed in the work of Duta and Henry [24]. In that way, the fused measurement of the compressor power can be obtained as:

$$\dot{W}_f = \lambda_1 \cdot \dot{W}_d + \lambda_2 \cdot \dot{W}_{id} \tag{10}$$

where coefficients λ_1 and λ_2 are obtained based on the model uncertainties, which was easily obtained after model calibration. The fused measurement of the condenser load was obtained in the same way as the measurement for the compressor power in Eq. (10), by using information on condenser model uncertainties.

3. CASE STUDIES

The Norwegian LTC procedures were tested on two office buildings in Stavanger and Trondheim, Norway. The case buildings are displayed in Figures 6 and 7. The first case building with 19 623 m^2 of heated area, as shown in Figure 6, is located in Stavanger, where design outdoor temperature is -9 °C [25], while the average annual outdoor temperature is 7.5 °C [26]. This first case building has been in use since June 2008. The second case building with 16 200 m^2 of heated area, as shown in Figure 7, is located in Trondheim, where design outdoor temperature is -19°C [25], while the average annual outdoor temperature is 6 °C [26]. The second case building has been in use since September 2009. Both case buildings are rented as office buildings.

Figure 6. Office building in Stavanger

Figure 7. Office building in Trondheim

The ventilation system concept is different in these buildings, while energy supply systems are similar. In the first case building, the ventilation system consists of three VAV systems, where the maximal air volume is 90 000 m^3/h for two ventilation systems, and 75 000 m^3/h for the third system. In the second case building, the ventilation system consists of eight VAV systems, with the maximal air volume from 12 500 m^3/h to 22 000 m^3/h. In both case buildings, heating is provided by radiators, while cooling is provided by fan-coils.

The solution for the heat supply in the consumer substations for both case studies is similar. Heating energy for ventilation, space heating, and domestic hot water is supplied by district heating and heat pumps. Cooling energy is supplied by two cooling plants. Heat realized from the cooling plant condensers is used as additional energy for heating. In that way these cooling devices are at the same time heat pumps. The only difference between the heat supply solutions in these buildings is that in the second case building, one cooling plant is only used for the ventilation systems, while the second cooling plant is used for fan-coils. In the first case study, two cooling plants are supposed to work integrated.

4. RESULTS

4.1. Amount of information

In order to perform any system estimation, it is necessary to know which information is actually available for further analysis. Therefore, in this part of the study assessment on the information amount was performed for these two case buildings, based on all the available data from different phases of the building lifetime. A qualitative overview on defined and found building functions for the office building in Trondheim is given in Table 2. The number of functions or building performance data is given for each system in the building. They were counted for each building system and at different phases of the building lifetime. In addition, Table 2 gives the number of common functions between different phases. Assessment of information amount was done by comparing the number of found functions at certain building level with the defined number of functions from LTC procedures.

Table 2. Number of building functions in office building in Trondheim

Table 2 shows that for the second case building the ventilation systems were presented with more performance data than the others. For example, it was possible to find 65% of defined performance data by comparing the installed performance data, which were found in the manufacturer technical guides, and the defined LTC performance data, from Table 2. In this case, it means that LTC procedures require in total 623 performance data for eight ventilation systems, while in the construction phase it was found 402 performance data for eight ventilation systems. There was a similar situation in the first case building, where there were 60% installed functions for the ventilation system.

The situation was opposite for the hydronic systems like the domestic hot tap water system, hydronic heating system, fan-coil system, and cooling systems. For example, the amount of the installed function were 20% of defined functions in the first case, while in the second case building there were 40% of defined functions, as shown in Table 2. This means that energy audit, inspection, and testing of these systems could be difficult. In total, about 20% of all the defined building performance data can be monitored by BEMS. There are only 10 - 20% of common performance data among different documents and building levels. This means that there is no generic framework among different building documents.

Using the Norwegian LTC procedures several findings were found on the two case studies. In the first case study, the results showed five findings due to that the Cx work did not start early in the design phase. These findings can be explained as: lack in documentation, system oversizing due to lack of information, poor functional definition, and poor functional integration. The poor functional integration means that the temperature sensors in the ventilation systems were related to the wrong temperature measuring points.

The second case building has been provided with a VAV system for every office. This implies that each office has a VAV and an air diffuser. The inspection of these VAV systems was done using the rule-based algorithms introduced in Chapter 2.2. Seven ventilation systems with 509 VAV units were tested. The inspection showed the following problems: possible noise problem on 10% of all the diffusers and lack of air on 3% of all the diffusers. The inspection of data from the balancing phase showed that 78% of measurements were correct, which means that measured amounts of air were in according to the design. The other finding on the second case building was that the installed heat pump, was oversized. Maximum demand from coils in ventilation system integrated to the heat pump was 91 kW, while the installed condenser capacity was 320 – 550 kW depending on the outdoor temperature. This installed heat pump was controlled stepwise in seven steps.

4.2. Results on mass flow inspection in the substation

The algorithm for the mass balance inspection was tested on the case office building in Trondheim. The inspection was performed for the consumer substation shown in Figure 8.

Labeling in Figure 8 is according to NS 3451 [17] and multidisciplinary labeling system established by the Norwegian Public Construction and Property Management [27].

Figure 8. Schematic of the consumer substation

The main branch, 320.001, supplies four branches for floor heating, radiators, snow melting, and ventilation system. Volumetric flow rates and temperatures in Figure 8 are from design drawings.

Data from the LTC procedures that were used for the mass balance inspection are given in Table 3. Data on the water flow rate in the design phase were found in the assembling drawings. Data from the construction phase are based on delivered equipment size and manufacturer technical guides. Data from balancing were provided from balancing reports.

Table 3. Water flow rates in kg/s found in different documents

If mass balance has to be established in the substation, then data in Table 3 have to satisfy Eq. (1). If we check data in Table 3, it is obvious that sum of mass flows in the branches 320.002, 320.003, 320.004, and 36.000 is not equal to the mass flow in the branch 320.001. Since data in Table 3 are only numbers, and there is assumption that there is no leakage, the conclusion is that the mass balance for data in Table 3 is not satisfied. However, the system will find its balance naturally. Therefore, it was necessary to estimate real mass flow using Eqs. (1) and (2). Estimated flow rates are given in Table 4.

Table 4. Estimated flow rate in kg/s

In contrast to Table 3, data in Table 4 are satisfying mass balance, Eq. (1). Overview of the calculated errors for each branch in Figure 8 is given in Table 5. Finally, use of error can help to detect where possible faults can appear in the system.

Table 5. Errors, mean error, and standard error deviation on the flow rate

Using the established rules for the mass balance inspection, it was found that in the branch for floor heating, 320.002, the water flow would be always higher than it was found in the documentation. Such difference in the mass flow implies difficulties in the control of the supply water temperature to the branch 320.002. BEMS data were used to analyze this issue. Measurement on the supply water temperature for the floor heating is shown in Figure 9.

Figure 9. Biased supply water temperature at the floor heating branch

In Figure 9, it is possible to notice that supply water temperature to the floor heating is most of the time biased and different than the desired value. This bias could be up to ± 1.5 K, when outdoor temperature was in the range of -3.5 – 7.5 ^{o}C. Since the floor heating is a low temperature heating system, with temperature difference on the supply/return side of 5 K, such big bias in the supply temperature could induce approximately an increase of 20% in energy consumption for the floor heating.

4.3. Estimated heat pump performance based on data fusion technique

The heat pump analyzed by the method introduced in Chapter 2.4 is displayed in Figure 10.

Figure 10. Heat pump in Trondheim office building

The heat pump in Figure 10 is water/air heat pump and it supplies eight heating/cooling coils in air handling units. Depending on evaporation and condensation temperatures, maximal heating capacity of the condenser can be 550 kW, and maximal compressor power can be 150 kW. During winter the heat pump supplies heating, while during the summer it supplies cooling to the coils. The heat pump has three compressors, which are step-wise controlled.

Using improved heat pump performance estimation, the compressor power and the condenser load were estimated. Firstly, the results of the direct and indirect measurements of compressor power and condenser load are shown separately in Figure 11. Afterwards, the fused measurements of the heat pump performance are shown in Figure 12.

Figure 11. Compressor effect and condenser load

The measurements of the condenser load in the first from the top figure in Figure 11 are obtained by using Eq. (5) for the direct measurement, and using Eq. (9) for the indirect measurement. The measurements of the compressor power in the mid figure in Figure 11 are obtained by using Eqs. (3) and (4) for the direct measurement, and using Eq. (6) for the indirect measurement.

Figure 12. Data fused heat pump performance

The fused measurements of condenser load are displayed in upper part of Figure 12, and the fused measurements of compressor power are displayed in lower part of Figure 12. When outdoor temperature is lower than -12 ^{o}C, the heat pump is not in use. The indirect and fused measurement showed that the heat pump was not in use. Estimation of the condenser load based on the data fusion technique, the red line in the upper part of Figure 12, shows no heating load at the condenser. However, estimation of the condenser load based on the direct measurement, the temperature difference, the blue line in the upper part of Figure 11, shows a certain heating load on the condenser. This difference happened because the circulation pump is always ON as a measure for freezing protection, and therefore a small temperature difference can give a certain amount of the heating load. Comparison of the measurements in Figure 11 and 12 shows that use of only direct measurement to estimate the heat pump performance can mislead us to treat that heat pump is running even when it is OFF. Comparison of the direct and indirect compressor power, the blue and purple line, in Figure 11 showed good matching between these two estimation methods.

4.4. Energy consumption

After necessary information to fulfill the LTC procedures were found, energy consumption of two case buildings was analyzed. Since the second case building is in use since June 2008, it was possible to get energy consumption for the entire 2009. Comparative results on calculated and measured energy consumption are displayed in Figures 13 and 14 respectively.

Figure 13. Calculated energy consumption for the case building in Stavanger

Figure 14. Measured energy consumption for the case building in Stavanger

Regardless of the above findings, the first case building achieved 9% lower energy consumption than calculated in 2009. This decrease in the energy consumption was due to better utilization of the heat pump and cooling plants. In this case, electricity consumption was quite independent of the outdoor temperature, but determined by building users. Hourly effect profiles in February and June are given in Figures 15 and 16, respectively. In Figures 15 and 16, hourly effect of electricity, heating and energy for tap water are displayed. These Figures are obtained by summing the effects.

Figure 15. Hourly effect profile in February for office building in Stavanger

Figure 16. Hourly effect profile in Jun for office building in Stavanger

In Figures 15 and 16 it is possible to note that electricity consumption is almost the same in the winter and spring period. Electricity consumption of the cooling plants is contributing to a small percent to the electricity consumption. Therefore, the electricity consumption is mostly determined by building users. Only heating consumption can be related to the outdoor temperature as shown before in [8].

The second case building has very well, detailed, and separated monitored energy use monitoring. In Figure 17 hourly profiles for Trondheim from 22nd through 28th February, 2010 are shown.

Figure 17. Hourly effect profiles for the case building in Trondheim

The results in Figure 17 can help to track energy consumption detailed. The measurements in Figure 17 correspond to the outdoor temperature in Figure 11. In the second case building, the office building in Trondheim, VAV systems are controlled by movement sensors, so fans were operating only when there were users in buildings. Therefore, the electricity consumption of fans was determined by building users. In addition, the inspection of the ventilation systems showed that most of the equipment was properly installed, so it was expected that the energy consumption should not have any deviation. In this second case building, only heating energy could be related to the outdoor temperature. Electricity consumption of the heat pump shown in Figure 10, was quite constant and low about 10 kW, the green line in Figure 17. The estimated compressor power in Figures 11 and 12 showed different results. The reason for this difference in the measurement of electricity consumption of the heat pump was poor functional integration. Actually, in this case building, BEMS and energy monitoring system are operated by two different companies. BEMS was delivered and operated by BEMS contractor, while an energy service company is in charge for energy monitoring. This example of the heat pump electricity consumption showed a need for better functional integration of building information and measurements. Specially, if there is a necessity to prove energy-efficient solution, then an accurate estimation is necessary.

5. CONCLUSION

The paper presents Norwegian LTC procedures that enable tracking and quality control of the building performance during the building lifetime. The performance tracking is enabled by establishing a generic framework on building performance. The LTC procedures were tested on two case buildings. The paper presents some of the reasons for integrating lifetime commissioning as an inherent part for energy-efficient solutions. As reasons to integrate lifetime commissioning into energy-efficient solutions development, the following were emphasized: building information collection, building performance monitoring and analysis, and energy consumption analysis. For each of these reasons, tools and examples were given in the paper.

The results on the case buildings showed several findings that can be explained as: lack in documentation, system oversizing due to lack of information, poor functional definition, and poor functional integration. In the case when lots of data are available, like 60 – 65% in the case of ventilation systems, it is possible to implement any rule-based algorithm to inspect a system. Further, 20% of all the defined building performances can be monitored by BEMS. Only 10% of common performances among different documents mean that there was no generic performance definition in the building documentation. Since building information loss induces performance degradation, LTC procedures are necessary to be a knowledge-based tool that can enhance collection of building performance. Regardless of leakage in data, it was possible to obtain useful information on building performance by combining available information and mathematical methods. By combining knowledge from the LTC and detailed energy monitoring, it was possible to easy detect faults in operation.

For efficient operation of energy-efficient solutions, it would be necessary to have quite higher monitoring level than current situation, special on the energy supply side. This need for enhanced measurement in the hydronic system and on the energy supply side was shown on the measurement on the heat pump and the consumer substation. Heat pump performance estimation can be more accurate using data fusion technique, where data from construction and operation phase were combined. Low temperature systems can be an example of energy-efficient system. Combining data from design, construction and operation phase, it was shown that a fault in the mass balance induced fault in the temperature control for the floor heating regardless of good intention. The results on energy monitoring showed that energy consumption cannot be related only to the outdoor temperature, yet several additional variables like building users have to be considered.

NOMENCLATURE

a_j	the entry/exit coefficient to the node
$C[-]$	clearance factor
$c_p\left[kJ/kgK\right]$	specific heat capacity
$m[-]$	exponent for heat exchanger
$\dot{m}\left[kg/s\right]$	mass flow rate
M	vector consisting of all the real estimated branch water flows
$p[bar]$	pressure
$\Delta p[bar]$	pressure decrease and increase before and after compression
$t[-]$	partial load of the compressor
$T\left[^{o}C\right]$	temperature
$UA\left[W/K\right]$	the overall heat transfer coefficient
$\dot{V}_S\left[m^3/s\right]$	the theoretical compressor volume
$\dot{V}_{air,pr}\left[m^3/h\right]$	desired air volume
$\dot{V}_{da,\min}\left[m^3/h\right]$	minimal air volume
$\dot{V}_{da,\max}\left[m^3/h\right]$	maximal air volume
$\dot{Q}[kW]$	thermal load
$\dot{W}[kW]$	power
$\gamma[-]$	isentropic coefficient
$\lambda_1[-]$	data fusion coefficient for the direct measurement

$\lambda_2\,[-]$	data fusion coefficient for the indirect measurement
$\mu\,[\%]$	mean error
$\sigma\,[\%]$	standard deviation of error

Subscripts

c	condenser
d	direct
dis	discharge
f	fused
FL	full load
i	indirect
$loss$	losses
out	outdoor
R	refrigerant
suc	suction
w	water
w,in	inlet temperature before the condenser
w,out	outlet temperature after the condenser

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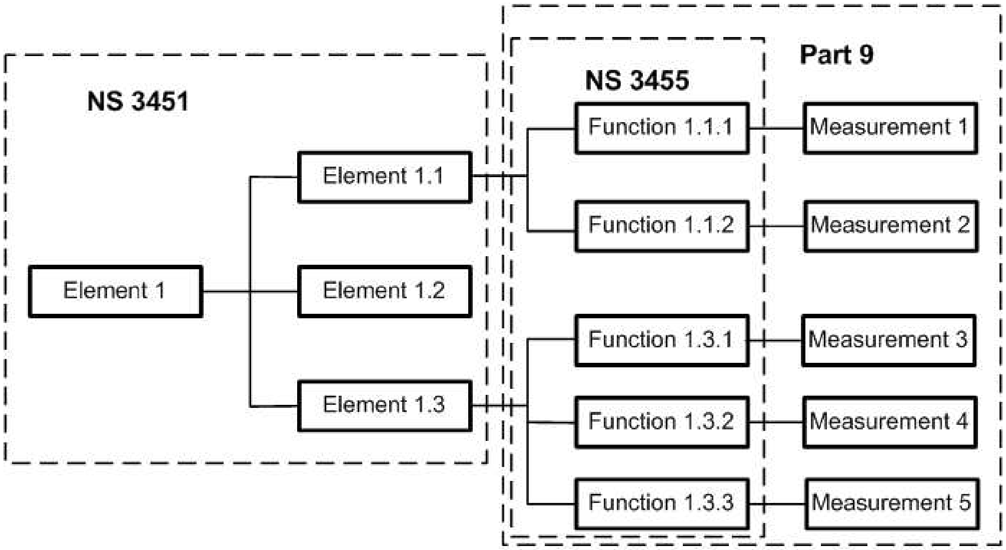

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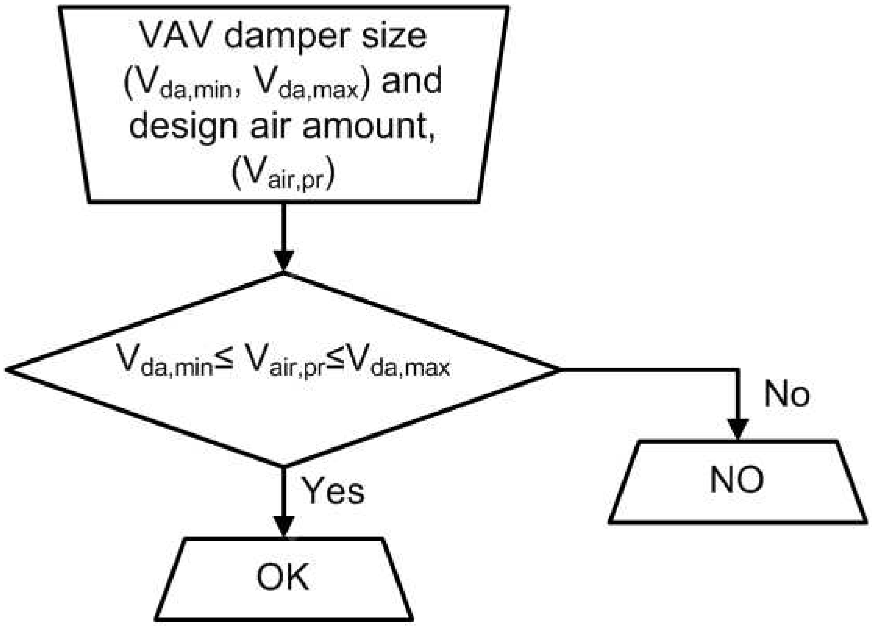

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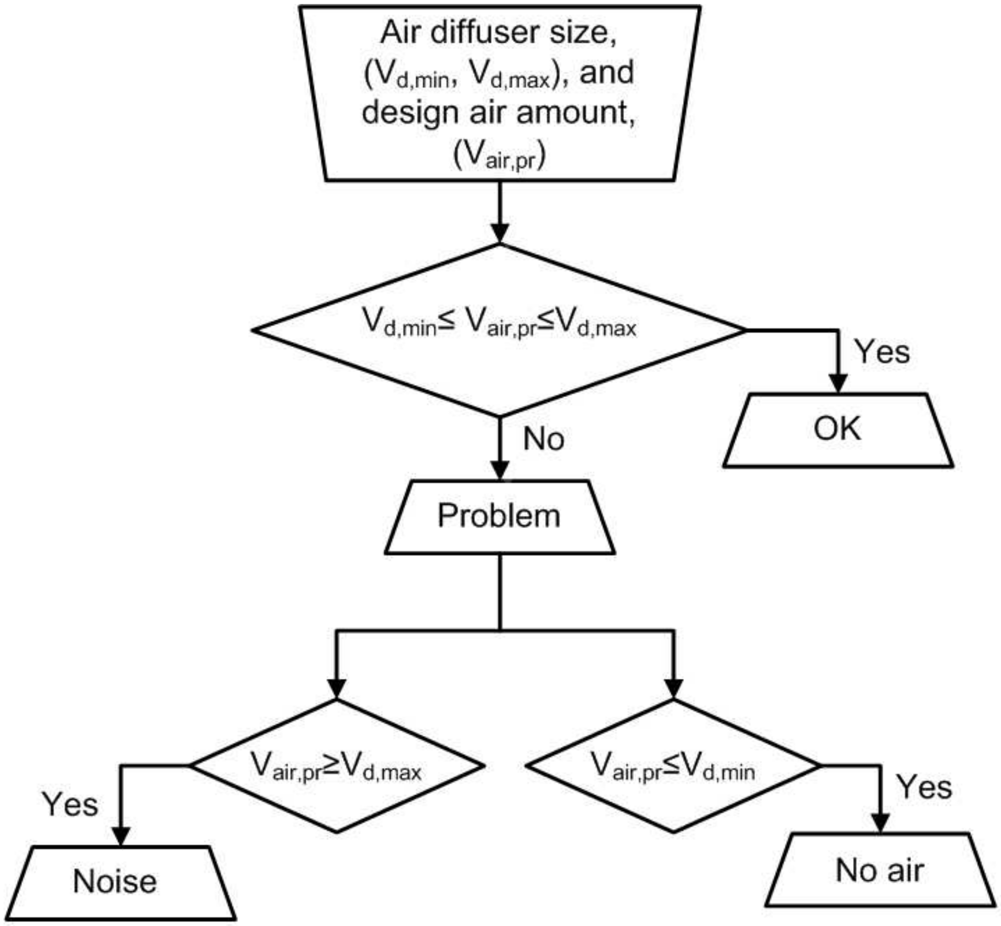

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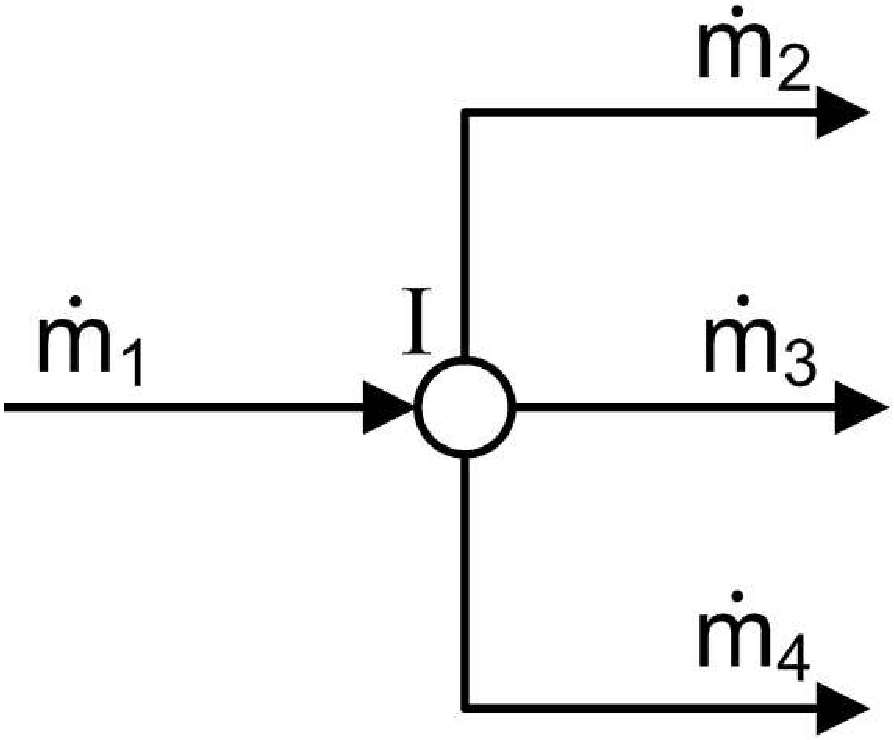

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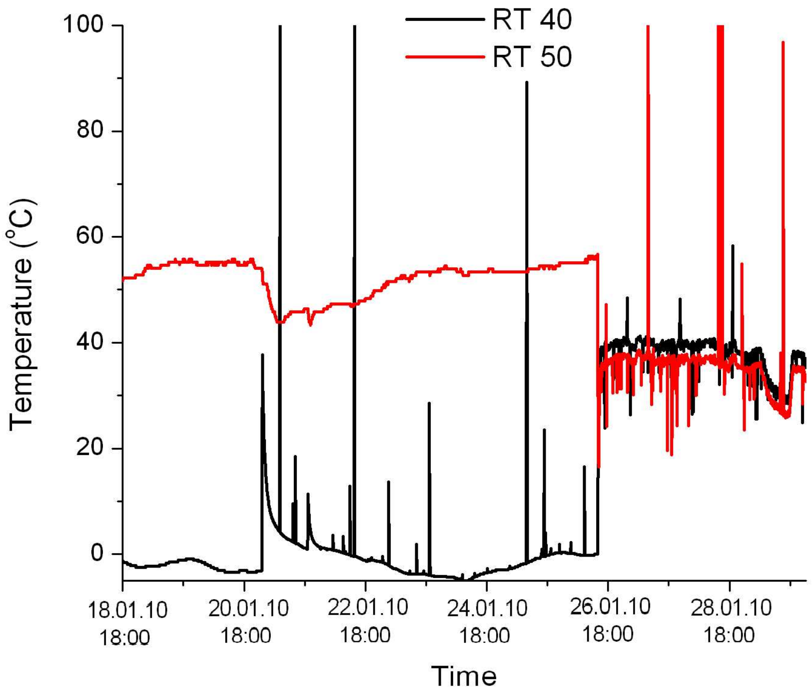

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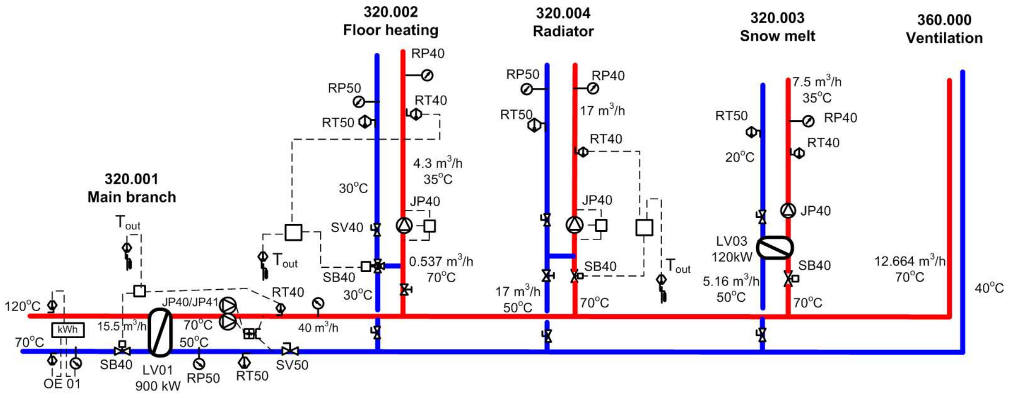

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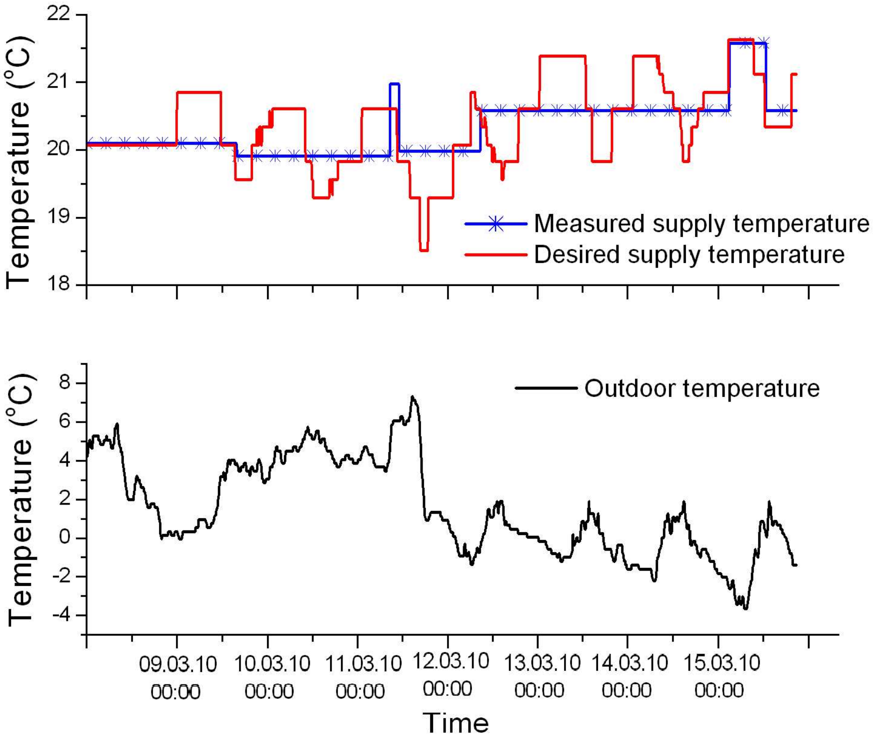

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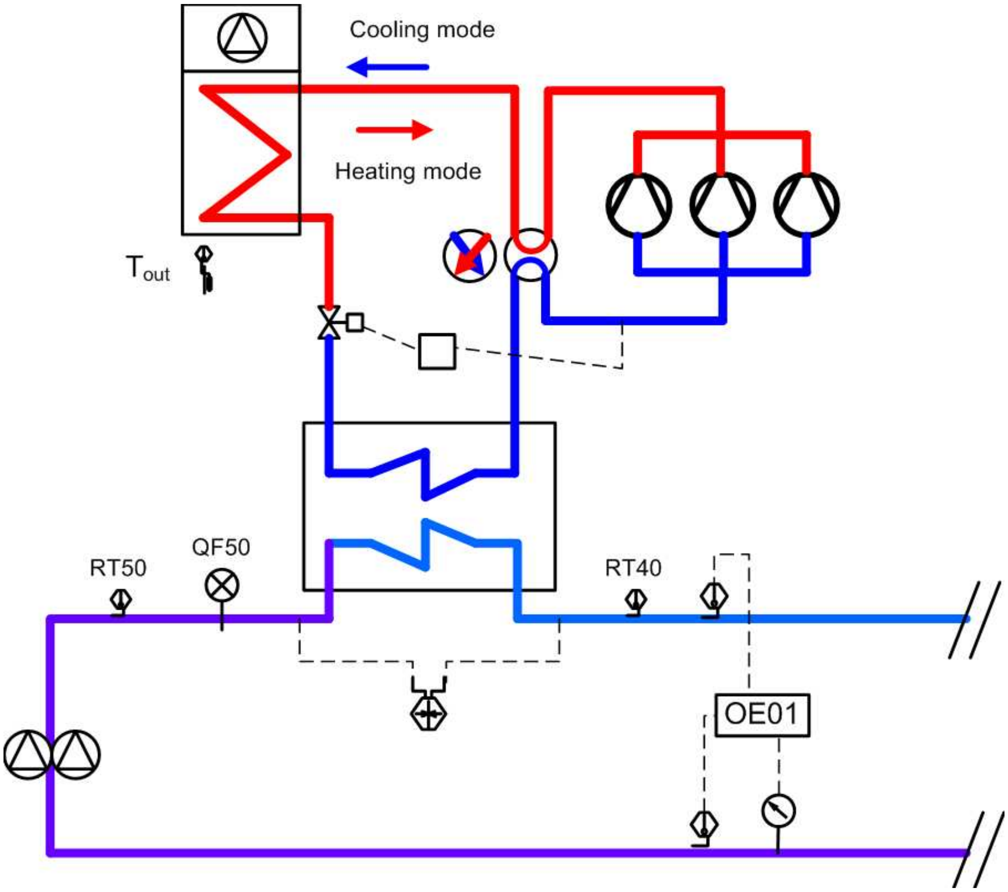

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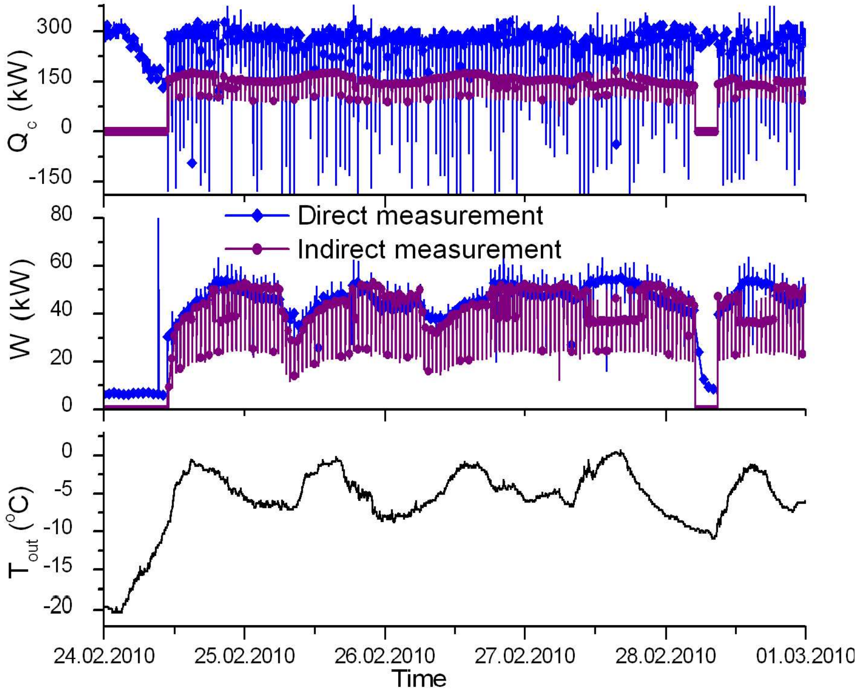

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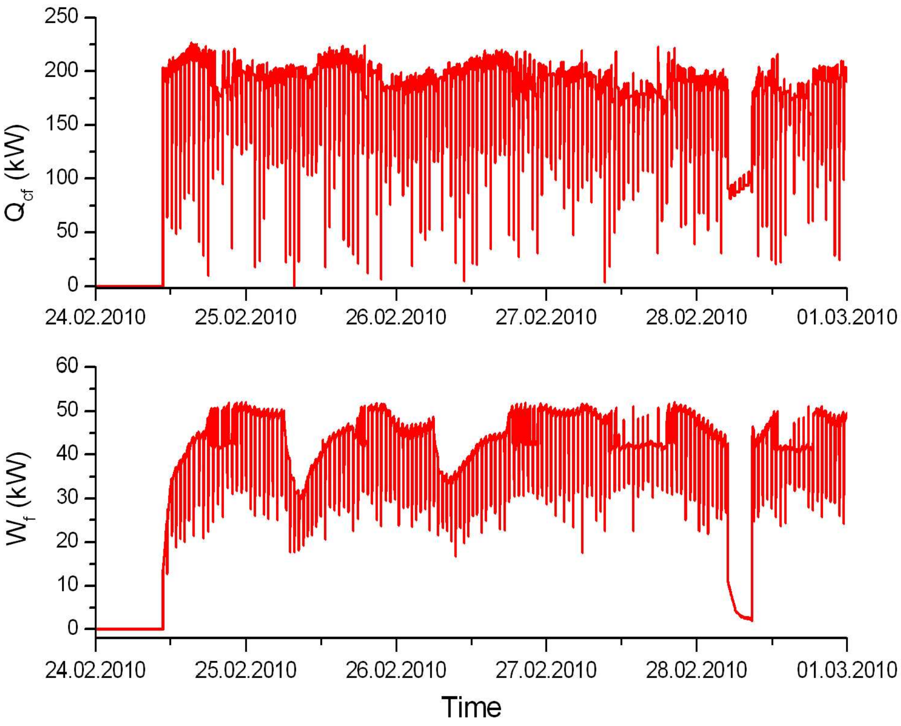

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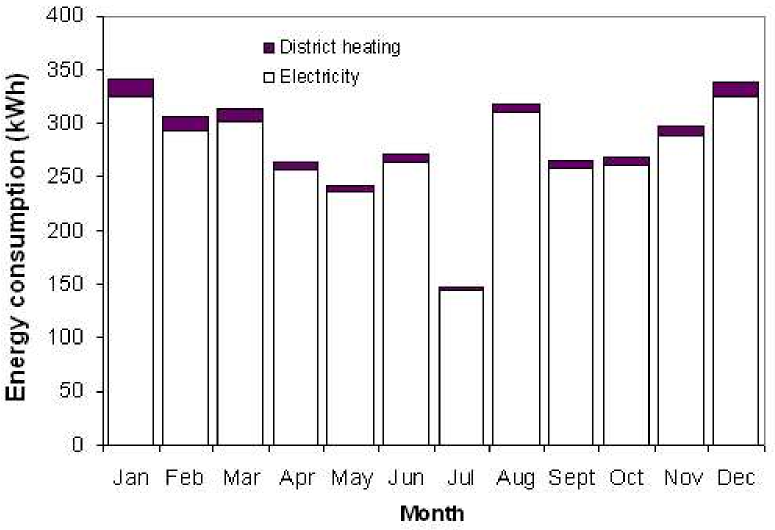

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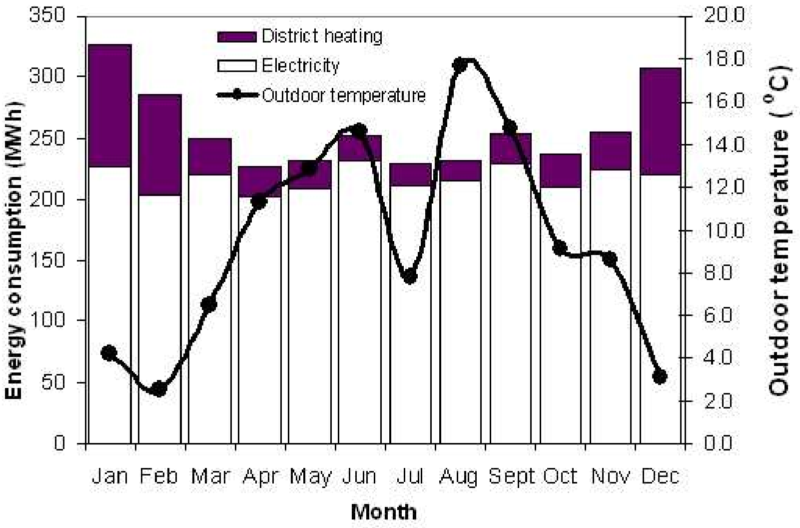

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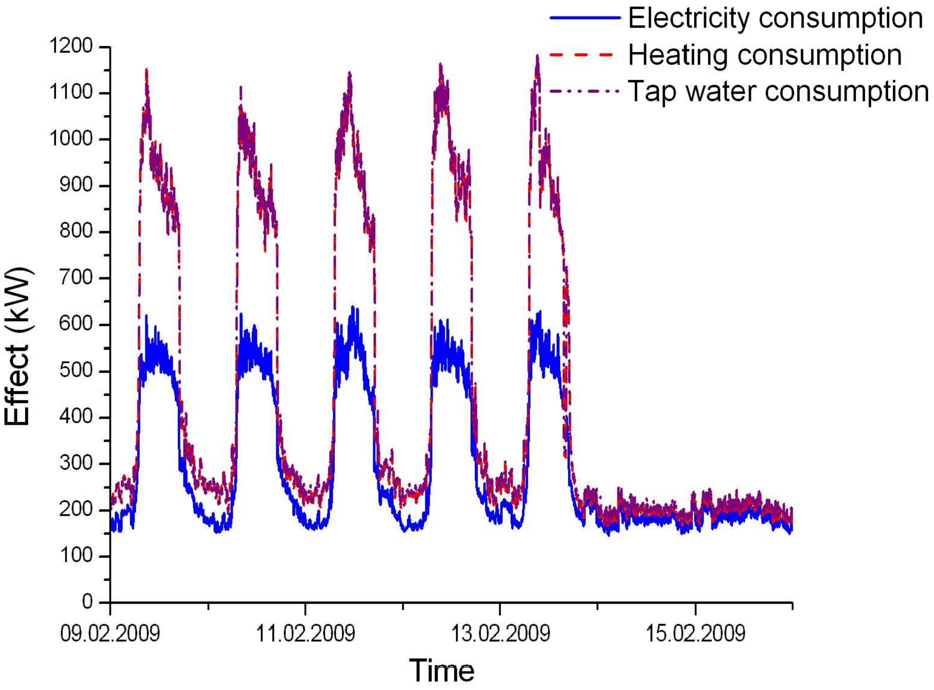

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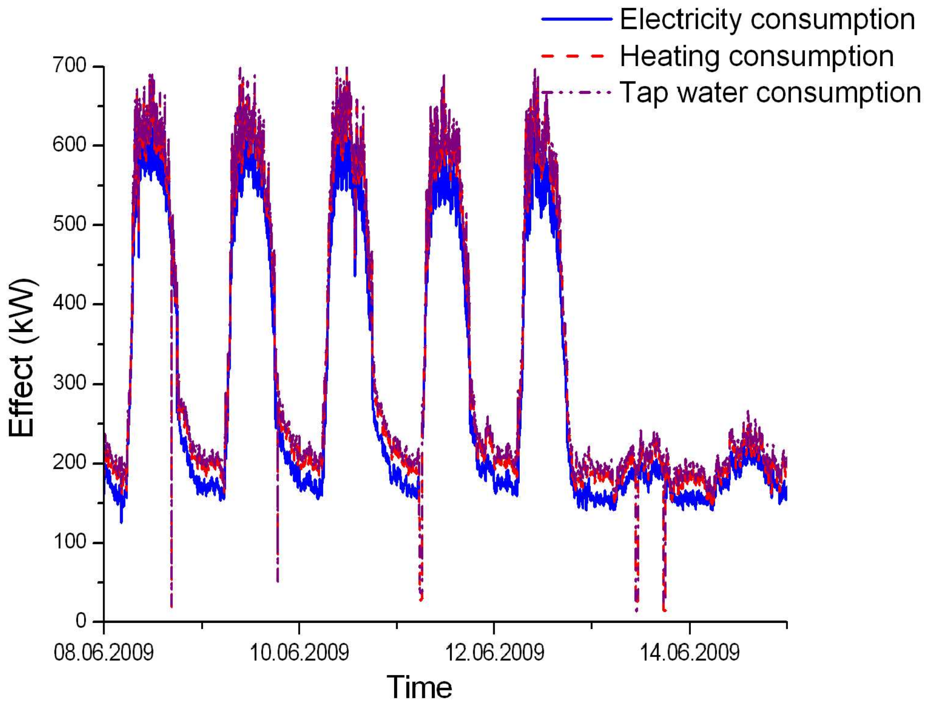

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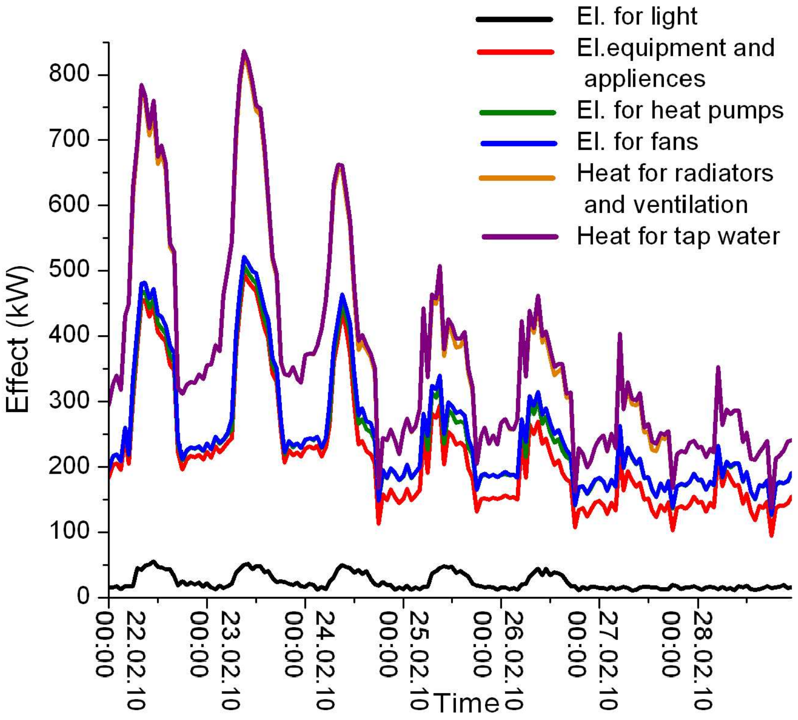

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Table 1. Norwegian LTC procedures structured into the building lifecycle

Part 1 Framework for the commissioning project	Design	Construction	Operation
Requirements	**Part 2** Performance requirements for Cx in the design phase	**Part 3** Performance requirements for Cx in the construction phase	**Part 4** Performance requirements for Cx in the operation phase
Plan	**Part 5** Plan for the Cx in the design phase	**Part 6** Plan for the Cx in the construction phase	**Part 7** Plan for the Cx in the operation phase
Common	**Part 8 and 9** Performance requirements and description		

Table 1. Number of building functions in office building in Trondheim

System	Purpose	Number of					
		Components	LTC functions	Design functions	Installed functions	BEMS functions	Common functions
313.010	Domestic hot water	5	21	2	12	3	3
320.001	Heating supply system	15	61	16	26	16	16
320.002	Floor heating	5	27	6	6	6	6
320.003	Snow melt	8	35	15	14	7	7
320.004	Radiator	5	27	6	6	6	6
35.01	Cooling plant	28	113	5	27	5	5
35.02	Cooling plant	24	100	14	24	8	8
36.01	Ventilation system	19	72	16	48	20	19
36.02	Ventilation system	19	72	16	48	20	19
36.03	Ventilation system	19	72	16	48	20	19
36.04	Ventilation system	19	72	16	48	20	19
36.05	Ventilation system	19	72	16	48	20	19
36.06	Ventilation system	19	72	16	48	20	19
36.07	Ventilation system	19	72	16	48	20	19
36.08	Ventilation system	27	119	22	66	20	19
	Total	250	1009	200	521	211	203

Table 1. Water flow rates in kg/s found in different documents

Branch / Phase	320.001	320.002	320.003	320.004	36.000
Design	10.92	0.15	1.41	4.64	3.46
Construction	13.16	0.15	1.44	4.64	3.84
Balancing	12.12	0.16	1.47	5.24	4.19

Table 1. Estimated flow rate in kg/s

Branch Phase	320.001	320.002	320.003	320.004	36.000
Design	10.62	0.42	1.61	4.89	3.70
Construction	10.79	0.42	1.62	4.89	3.86
Balancing	10.95	0.27	1.53	5.06	4.09

Table 1. Errors, mean error, and standard error deviation on the flow rate

Branch Phase	320.001	320.002	320.003	320.004	36.000
Design	2.72	-64.94	-12.71	-5.14	-6.52
Construction	21.62	-64.94	-11.42	-5.14	-0.38
Balancing	11.46	-41.29	-3.40	3.59	2.48
μ	11.93	-57.05	-9.18	-2.23	-1.47
σ	9.46	13.67	5.05	5.04	4.60