Correlation between standards and the lifetime commissioning

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Abstract

This paper reviews the applicability and drawbacks of available European and international standards related to lifetime commissioning, by structuring them into Norwegian commissioning procedures. The work describes research on lifetime commissioning that proposes a generic framework on building performances. The generic framework describes a component in HVAC system by performances. The results of the standard review show that there is a need for measurement and testing standards in hydronic systems. In addition, there is no generic framework on the definition of energy-efficiency measure in the reviewed standards. Findings on a case study, where lifetime commissioning procedures were tested, are presented. After the performances of the case study were defined by the generic framework, it was found that 20% of all the performances can be monitored by a building energy management system. Due to good operation, the building managed to achieve 3% lower energy consumption than design a year after the building was taken in use. In addition, results show that energy signature curves can be used only in a modified way to predict heating consumption, while electricity consumption can not be described in that way.

Keywords: lifetime commissioning; generic framework; building performance; standards

1. Introduction

Buildings are becoming more complex systems with many elements, while building energy management system (BEMS) provides much data about the building systems. There are, however, many faults and issues in building performance, but there are legislative and cost-benefit forces induced by energy savings [1]. To overcome these problems and challenges, it is necessary to have a tool that can help to provide quality control on building energy performances, to perform fault detection and diagnosis, and overcome poor functional integration induced by information loss. Lifetime commissioning (LTC) has been recognized as a tool that can perform these given tasks [2-4]. A survey on commercial buildings in southern California showed that 42 of the 72 organizations had developed documents that addressed the commissioning process [5]. 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 the study, LTC is treated as performance verification. Also, LTC is described as performance verification in the work of Kjellman et al. [5]. The first aim of this study is to present the Norwegian LTC procedures. These procedures are presented by a proposed method for expressing building energy performances during the building lifetime. Such a method imposes a generic framework for the building energy performances.

According to the Norwegian LTC, commissioning work should be done by a new role named *Cx responsible*. A *Cx responsible* is responsible to realize 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 [7]. Similarly, the Norwegian standard NS 3935, ITB Integrated technical building installations, Designing, implementation and commissioning [8], shows a need for an ITB responsible person.

A building process is typically split into fragments with different players. By changing the players within the building process, important information can be lost. 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]. The same can be said for the building operation and maintenance sector. There experience is a useful tool for enhancing building operation. Regardless of the issue that information loss induces performance degradation, there are few literature sources that explain it. In the work of Lee and Akin [10], it was found that there is a 12% potential for the maintenance improvement by providing proper information support. Therefore, the purpose of the Norwegian LTC procedures is to be a knowledge-based tool that can enhance collection of building performance information.

Many standards give guidance to requirements on building performances, measurements and inspection, while the LTC can verify these requirements. Diversities among standards for requirements, inspection, monitoring, testing, and energy management are: responsible person, purpose, duration and person or institution who requires the service. Regardless of all these diversities, the same data are used for different purposes. Therefore, LTC as performance verification tool has to give an information framework on the building energy performances by utilizing information from relevant standards. Norwegian LTC procedures have been developed to collect building data, so that follow-up of the building performances is enabled during the entire building lifetime.

Energy labels on buildings are mandatory in European Union since 2006 with the application of the European directive 2002/91/CE [11] on the energy performance of buildings. Therefore, in the last years, have been developed many standards related to the building energy performances. The objective of this Directive is to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness [11]. However, after few years of the application of Energy Performance of Buildings Directive (EPBD), some issues have been found. For example in the work of Szalay [12], two main problems, the integrated energy performance and omitted lifecycle energy balance are mentioned. The first problem means that energy performance is expressed in a complex way, including many components that are not directly related to the building [12]. A study on how the labels work in Belgium shows that only 11% of all proposed energy-efficiency measures have been implemented one year after the energy assessment by the 40 households because the building users do not well understand the label. However, information on cost of investment and possible savings imposed by a given measure can encourage building users to implement measures [13]. Therefore, the second aim of this study was to review the relevant European standards. Afterwards, the relevant standards were mapped in the proposed framework for building performances so that the data from standards could be compared with data defined in the Norwegian LTC procedures. In that way it could be possible to realize lacks in the current standards and need for new standards.

In this paper, the presentation of the Norwegian LTC procedures and review of the standards were done by using proposed generic data framework for the building energy performances. Since LTC is a tool for the performance verification and the reviewed standards define building energy performance, building energy performances are common items in the proposed framework. Therefore, the entire data framework was developed to track building performances. A methodology named energy performance assessment for existing building (EPA-ED) developed in line with EPBD and supported by software shows that a uniform way of presenting building energy performances is necessary to achieve easier integration of new standards into EPA-ED [14]. The study of Xu et al. [15] shows that major difficulties in evaluating building energy performance in China are the shortage of good benchmark energy consumption data and disparity in building services and operating conditions. These two studies show a big need for a generic data framework on the building energy performances. Such a generic data framework would give us the advantage that any system change during the building lifetime can be easily noted.

This paper consists of four parts. The first part presents the Norwegian LTC procedures together with the proposed generic information framework on the building energy performances. The second part reviews relevant European and international standards by mapping them into the framework. Findings in a case study discovered using the procedures are explained in the third part. In addition, the third part gives energy consumption of the case building. Deficiencies in the current standards and the need for new standards are presented in the fourth part.

2. Norwegian LTC procedures

The Norwegian LTC procedures for improving building performance were developed based on international commissioning experiences and national practical experiences. The procedures are a manual and consist of nine parts. They are available in Norwegian. The aim of the procedures is to create a good information system between all the participants during the building lifetime.

Since the commissioning process must start early in the design process, these Cx procedures have been developed to start before the building programming phase. The focus is on ensuring the owner's project requirements so that the performance verification is possible in an early stage. In addition, the focus is to develop uniform verification checklists and pre-functional test procedures that ensure proper equipment installation and function. These procedures are written for a generic project and have to be adapted for each Cx project.

2.1. Model description

The Norwegian LTC procedures are manual procedures, where framework for describing building performances can be explained as a data model. As a building lifetime is proceeding, activities described in a certain document have to be fulfilled. These procedures consist of the following parts:

- Part 1: Performance requirements for the LTC;
- 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;
- 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;
- Part 8: Requirements list for the Cx;
- Part 9: Performance description.

Table 1 maps the above parts in the building lifecycle that consists of design, contraction, and operation phases. A Cx activity can be described by setting requirements and planning fulfillments of the given requirements. Therefore, Table 1 gives a classification of the above documents by their purpose and phase in which the documents are supposed to be used.

Table 1. Mapping the Norwegian LTC procedures into the building lifecycle

Based on the building owner requirements, a supervision plan has to be established by using Part 1. In Table 1, Part 1 is in the left upper corner, because that one gives a framework for the activities defined in the other parts. Part 2 and 5 correspond to each other. For example, based on valid standards and the owner requirements, a list of requirements should be developed according to Part 2 in the design phase, and then according to Part 5 a plan for fulfillment of the requirements has to be given. Together with this inspection in the design phase (Part 2 and 5), a list of necessary requirements on performances has to be developed according to Part 8. According to Part 9, performance description has to start by developing early in the design phase. This performance description implies actual follow-up performances defined according to Part 8. Part 8 and 9 can be one document, but they are separated to make a clear difference between performance requirements and achieved performance in operation. As shown in Table 1, required information according to Parts 8 and 9 are common for the entire building lifecycle. Based on Part 2, requirements in the construction phase have to be developed according to Part 3. Based on manufacturer requirements and available testing standards, requirements in the operation phase have to be developed according to Part 4. Similarly as Part 5, Parts 6 and 7 give a plan for fulfillment of the given requirements in the appropriate phase. There is no practical need to document all the activities and information described in each Part of the LTC procedures. Plans according to Parts 5, 6, and 7 are not necessary to document, while performance requirements and their description should become an integrated part of building information system. The performance requirements, which are developed according to Part 2, 3, and 4, build documentation of Part 8. In the work of Ozkaya and Akin was explained that one requirement object in one design session may instantiate a design component; in another session the same requirement object may instantiate multiple design components [16]. Similarly, in these procedures the requirements from one phase induce requirements in the next phase. Finally, all the requirements have to be collected in the common document. Documentation of Part 9 implies enabling the monitoring of the building performances through the building lifetime, therefore this documentation is extending through the entire lifetime.

2.2. Framework for building performances

Practically, the necessary information for fulfillment of the LTC procedures can be collected in different ways. Here a framework for collecting building performances is presented. This framework describes building performances as a data model. Therefore, overview on the requirements and performances can be established in a spreadsheet or database. The idea to collect building information as data model came from NS 3451, Table of building elements [17] and NS 3455, Table for building functions [18]. According to NS 3451, a building is defined as a list of items and sub-items, which are building elements and components. Building description by using NS 3451 is widely practiced way in the Norwegian building industry. Use of NS 3455 in the construction phase will improve the possibilities for quality control of projects under plan and design phase [18]. Table of building elements is adequate to use for describing the requirements on building technical characteristics, while Building functional tables are the most adequate to describe requirements on functional characteristics [19]. Even though these standards are dealing with building elements and functions, there is no document that connects them. Therefore, in our framework for collecting building performances, we suggest a simple way to connect the elements and related functions as shown in Fig. 1. A building performance is a function of a building element, which can be defined by a few performances.

Fig. 1. Relationship between building elements and functions

Fig. 1 shows an example of a generic framework on building performances. A building element can consist of a few sub-elements (in Fig. 1 three elements), which can be defined by a few functions. For example, fan functions can be: air flow rate, pressure difference, motor power effect, and the specific fan power (SFP). The function numbers of an element depends on the element specification and which performances are necessary for performance estimation. As shown in Fig. 1, the building elements should be defined according to NS 3451, while building performances are related to NS 3455. Finally, the documentation of Part 9 from the LTC procedures can be established. To follow-up each desired function, it is necessary to define measurement of that function as shown in Fig. 1. Therefore, measurement of desired performances should be defined as soon as an element performance is involved in a building project.

This suggested framework on building performances enables generic definition of performances and their requirements. In that way different manipulation on performances is enabled for different purposes. The work of Garrett mentions that each basic requirement is mapped to a unique generic behavior limitation and stated in terms of criteria for its applicability as well as the traditional performance criteria [20]. If building performances are defined by using suggested framework in Fig. 1, then each performance will have one requirement and mapping of the requirements is enabled, similarly as in [20].

2.3. Example of the framework for building performances

An example of the performance framework description of a branch in a heating system is shown in Table 2. Before the performances are presented, the scheme of the heating plant is given in Fig. 2. This heating system is an indirect connected system that supplies three radiator branches, three heat exchangers for ventilation systems and domestic hot water system. Labeling in Fig. 2 was done according to NS 3451 and multidisciplinary labeling system established by the Norwegian Public Construction and Property Management [21].

Fig. 2. Scheme of a building heating plant

The entire heating plant, 320.010, is consisted of 17 elements that can be described by 84 functions. Presentation of all these 84 functions is cumbersome; therefore, Table 2 is giving performances only for the system 320.012, the radiator branch - South.

Table 2. Performances of Radiator branch - South

14 performances for three components and four general performances are defined in Table 2. These performances were defined based on the suggested generic performance framework as in Fig. 1. The performance names are unique and defined related to both the system and function name. For example, 320.012.T40 is the supply water temperature of the system 320.012. The component names, SB for control valve or JP for pump are chosen according to [21]. In Table 2, by general functions are meant the performances that are important for system assessment, but are not supposed to be recorded as performances of the given components. The system 320.012 is presented by the given 18 performances, which were found in the different building documentations. The design data were found in assembling drawings and principal schemes. Data for construction phase are found in producer technical guides.

The column measurement in Table 2 shows where we can either get the value of performance or the appropriate sensor name. For example, the value of the supply water temperature is measured by the sensor RT 40, and this value can be read in the BEMS in a board named 434.005. Since some of the performances have the same function, their names are the same. In that way, the inspection of the performances in one phase is enabled. For example, the value of the water flow rate, 320.012.VM40, is used four times in Table 2, while three values are found in the building documentation. By using these values, it is possible to perform project inspection. The value of the water flow rate provided from assembling drawings, 8.4 m^3/h, is higher than the value found in the principal scheme, 8 m^3/h. The reason for this discrepancy can be that different persons developed drawings without comparing information. The example in Table 2 shows the necessity for LTC work and generic performance definition for the purpose to get desired building performances.

Fig. 2 and Table 2 show how Norwegian LTC procedures relate the schematic of the system with the system energy performances. Similarly, EN 15239, Guideline for inspection of ventilation systems [22], requires the schematic of the installation in the description form of the installation. This means that an inspection report could be issued immediately upon request, if the LTC work would be initiated early in the design and maintained during the building lifetime by establishing a performance framework.

Table 2 only gives a generic framework on building performances before the operation phase. Since performance values in operation phase are time-dependent, a new sheet should be developed for them. By linking from Table 2 to this new sheet, it is possible to check performances. After the generic framework is developed it is possible to use the performances for different purposes: inspection, fault detection and diagnosis, and optimization.

3. Mapping existing standards

As mentioned in the work of Garrett [20], standards should not be simply used as passive checking instruments, but instead treated as sources of knowledge used to derive structural component property values. Therefore, this part of the study aims to map relevant standards for LTC into the suggested generic framework. In that way relevant standards for performance requirements or inspection can be related to appropriate performances in a certain phase of the building lifetime. European and international standards were reviewed and mapped for the purpose of this study. EPBD lays down, among else the following requirements: the application of minimum requirements on the energy performance of buildings, energy certification of buildings, and regular inspection of boilers and air-conditioning systems [11]. This means that given performance requirements should receive a quality control. Since LTC has been recognized as a quality control tool, standards developed to support EPBD have been found relevant for LTC.

To utilize information from relevant standards into LTC, it is necessary to find a common information framework on the building energy performances between LTC procedures and the relevant standards. Standards differ in the method by which they specify adequate performance:

1. performance standards state minimum requirements on an entity;
2. procedural standards provide procedures for evaluating performance;
3. prescriptive standards state the required properties of an entity [20].

This standard classification and generic framework on building performances proposed in Section 2.2 have in common the following:

- building elements and functions are defined by prescriptive standards, NS 3451 and NS 3455;
- to fulfill the performance framework, it is necessary to know the performance requirements from performance standards;
- performances from the generic framework can be used by procedural standards to provide system assessment;
- consist of the same entity, building performance.

Based on the above approach, European and international standards are classified according to which performances are treated in the standards and for which purposes. The classification has been established for ventilation system, air-conditioning, and boiler and heating systems.

During the review of the relevant standards two issues were found in mapping the standards for the purposed generic framework:

1. definition of a requirement on the performance and on the equipment;
2. definition of the energy-efficiency measures.

EN 13779, Performance requirements for ventilation and room conditioning systems [23], requires the use of heat recovery. Heat recovery is equipment with certain performances, however, this is not listed in this standard. Therefore it has been difficult to extract the performances as a unique entity. Further, in most of the standards for the inspection, EN 15239, EN 15240, Guidelines for inspection of air-conditioning systems [24], and EN 15378, Inspection of boilers and heating systems [25], it is noted that based on the inspection results improvement advices should be given. This means if there is a deviation in an observed performance, improvement advices should be given. Opposite, by implementing the improvement advice, an improvement should be achieved on the observed performance. However, in these inspection standards, advices are given on the equipment. For example, in EN 15378, there are many lists for the improvement on the sub-systems, improvement of boiler, burner, space heating emission, etc. But there is no clear instruction which performances are improved. Only in EN 15603, Overall energy use and definition of energy ratings [26], it is noted that the improvement measures should be related to the energy performances. If all the improvement advices will be related to the building energy performances, then these advices can be easily mapped in the purposed generic framework.

A mapping of the standards related to the ventilation system is given in Table 3. Instead of the quantitative values in Table 2, Table 3 is listing the standards that are related to a certain performance at different phases of the building lifetime.

Table 3. Mapping the relevant standards to the ventilation system

In Table 3, there is a requirement on few performances in ventilation system defined by EN 13779, while the inspection of them should be done according to EN 15239. Further the inspection standard is referring to the measurement methods defined by EN 12599, Test procedures and measuring methods for handling over installed ventilation and air conditioning systems [27]. In addition, in EN 12599 it is defined to prove the system operation according to the specification, and the aim with the control measurements is to ensure that the system achieves the specified conditions and desired values [27]. Therefore, EN 12599 can be closely related to some of the lifetime commissioning aims. ISO 12569, Determination of air change in buildings [28], gives method for measurement of air change. EN 15232, Impact of automation, controls and building management [29], is giving the overview which performances are necessary to be monitored in order to calculate the efficiency of the control system. Table 3 shows that air change is a common performance for these four standards, EN 13779, EN 15239, ISO 12569 and 15232. This means that air change can be inspected by referring to the requirement and compared to the measured value or monitored value. This enables inspection on this performance. Empty fields in Table 3 mean that there is no standard to cover performances at a certain phase.

Table 4 is listing relevant standards for air-conditioning system. By ‘air-conditioning system’ is meant a combination of all components required to provide a form of air treatment in which temperature is controlled or can be lowered, possibly in combination with the control of ventilation, humidity and air cleanliness [11]. There are 11 common performances among the standards that are treating air-conditioning system.

Table 4. Mapping the relevant standards to the air-conditioning system

There are few standards that are treating air-conditioning system as shown in Table 4. Compared with Table 3, there are fewer defined performances for the air-conditioning system than for the ventilation system. Four performances, cooling load, operation mode, running time, and pressure drop on the water side, are common among EN 15240 and EN 15232. Table 4 shows that the inspection and monitoring of the air conditioning system is defined, but not requirement and measurement.

Finally, the relevant European standards related to boilers and heating systems are listed in Table 5. There are only two standards, EN 15378 and EN 15232, with 10 common performances that appear in this table.

Table 5. Mapping the relevant standards to boilers and heating systems

The most occurred standard in Table 5 is EN 15378. This standard is quite comprehensive and gives the inspection requirements and measurement methods as the standard annexes. There are two deficiencies among the two referred standards. The first one is that there are few common performances among these standards. In fact, there is no common performance among inspection, measurement, and monitoring. There are only two common performances between inspection and monitoring. These are operation hours and circulation pump maximal rated power. This means that the inspection can be done by using monitoring system for only these two performances. The second deficiency is that there is no method for hydraulic measurement.

After all the relevant standards are mapped into Table 3, 4, and 5, it is possible to assess the amount of data defined by the standards. The assessment can be done by comparing the total number of cells with the cells filled with the standards in the above tables. Thus, in Table 3 the ventilation system is defined by 12 performances at four phases, and there are 28 performances defined by standards. Therefore the ventilation system performances are 58% covered by standards. Similarly, the air-conditioning system performances are 34% covered, and boiler and heating system performances are 42% covered. The reason for low performance covering of the air-conditioning system can be found in the standard explanation. There is mentioned that it is not the intention to have a full audit of the air-conditioning system but a correct assessment of its functioning and main impacts on energy consumption [24]. However, there is a need for measurement and testing standards for these systems, because certain aspects of the inspections may be simplified or reduced, if there is evidence of a good maintenance as mentioned in [24]. A good maintenance practice can be carried out by implementing LTC procedures.

4. Test of the LTC procedures

4.1. Description of the case building

The case building, Fig. 3, is located in Stavanger, Norway where design outdoor temperature is -9^{o}C [30], degree-day is 3488^{o}C·day [31], while the average annual outdoor temperature is 7.5^{o}C [32]. This building has been in use since June 2008 and is rented as an office building. The heated area of the building is 19 623 m^{2}. The ventilation system consists of three variable air ventilation systems, where the maximal air amount is 90 000 m^{3}/h for two ventilation systems, and 75 000 m^{3}/h for the third system. Heating is provided by radiators and ceiling panels, while cooling is provided by fan-coils. Heating energy for ventilation, space heating, and domestic hot water is supplied by district heating and a heat pump. 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 plants are at the same time heat pumps.

Fig. 3. Office building in Stavanger, Norway

The LTC procedures have been tested on this building after the building was taken in use. To collect all the building information, the suggested framework on the building performances, as described in Section 2.2, has been implemented. A qualitative overview on defined and found building functions is given in Table 6. The number of functions is given for each system in the building. They were counted for each building system and at different phases of the building lifecycle. In addition, Table 6 gives the number of common functions between different phases.

Table 6. Number of building functions

For each system in Table 6, the performances were defined in the same way as done in Table 2 for system 320.012, heating branch for South block of the building. The LTC procedures require 18 performances to define this system, while three are defined in the design phase and five are measured by BEMS. To establish an energy and mass balance equation on the fan-coils, 14 performances were defined, while there are no data or measurement on them in the documentation. The reason for this is that the systems 350.012, 350.013, and 350.014 were extended afterwards, according to building demand. Actually, the contractor of the HVAC system gave a possibility for the system extension by installing additional cooling branches. However, neither in the design nor in any documentation was it possible to find information on fan-coils. This example shows that the framework on the fan-coil performances could help ease system integration and extension. Further, Table 6 lists the ventilation systems. Regardless of the other systems, the ventilation systems have been represented with more performances than the others. In total, 20% of all the defined building performances can be monitored by BEMS. Among these monitored performances, almost half belong to the ventilation systems. The domestic hot tap water system, fan-coil system, and partially cooling system are poorly defined. This means that energy audit, inspection, and testing of these systems could be difficult. Table 6 shows that even though 59% of all the defined performances can be found in the different documents, there are only 10% of common performances among different documents and building levels. This means that there is no generic framework among different building documents. This can discourage any attempt to track building performances during the building lifetime.

4.2. Findings in the case study

After all the building performances were defined according to the suggested framework, five findings were reported. The first one is that there was no principle scheme on the fan-coil system even though that was the requirement based on standard [22]. This means that inspection of the systems 350.012, 350.013, and 350.014 can be difficult. In addition, it was not possible to get an overview of the system performances as shown in Table 6 due to the very low number of defined performances of these systems. The second finding was related to system 313.010, the domestic hot water system. The principal schemes of the domestic hot water in the design phase showed that the domestic hot water was warmed up by district heating and two electric boilers. In reality, there was no electric boiler for heating up the tap water. Even though the system 313.010 is complex with two heat exchangers and one water accumulator, there were only two monitored performances as shown in Table 6.

The third finding was discovered by reviewing the report on the water system balancing. There were different water flows in the balancing report from the values in the design phase. An example of this difference is shown in Table 2 for the water flow of system 320.012. After the balancing, the branch water flow is 8.3% lower than the water flow in assembling drawings or 3.7% lower than in the principal schemes. This difference appears due to a change in the system supply water temperatures, particularly the branch supply temperature 320.012.T40 and the heating system 320.010 supply temperature. A decrease in the water flow after balancing means that the system was oversized. The system is designed based on a repeated experience without taking into consideration changed conditions. This third finding showed a need that Cx should start early in the design phase so that important data are stored and used when necessary. The fourth finding was related to the ventilation systems, 360.010, 360.011, and 360.012, where SFP of the exhaust fans was only monitored in the BEMS. There were two fans in each ventilation system, one supply and one exhaust fan. There is a requirement by three standards (EN 13779, EN 15239, and EN 15240) that SFP should be documented. Consequently, SFP can be reported immediately upon request for the exhaust fans, while for the supply fans, additional measurement and calculation should be done.

The fifth finding was a poor functional integration of temperature sensors in the ventilation systems. Air in the ventilation system is conditioned by an installation that integrates coil and recovery unit as shown in Figure 4. In the winter period, if there is not enough energy provided from the exhaust air, additional energy is provided from the district heating system by an additional heat exchanger. The same is true for the summer period, when necessary cold water is provided from the central cooling system. Fig. 4 shows two schemes of the same ventilation system with the same temperature sensors on different positions.

Fig. 4. Poor functional integration

The poor functional integration in Fig. 4 means that sensors GT 40 and GT 42 in the BEMS were showing the wrong temperatures. For example, GT 42 is the sensor for the freezing protection and measures water temperature after the exhaust coil that is part of the integrated coil and recovery unit. In the BEMS this sensor function is marked to measure the water temperature after the additional heat exchanger. This fault in the functional integration occurred due to different contractors for the ventilation system and the control system. In addition, the temperature sensors are marked by GT, while according to the multidisciplinary labeling system [21] they should be marked by RT. Even though this fault seems to be minor, in the case of operation personal change, knowledge about the system can be lost and measurement of these sensors can be misunderstood.

4.3. Energy consumption of the case building

To get an overview of the case building, energy consumption was also analyzed. Since electricity, heating, and cooling energy are consumed by the building, they were measured and compared with the design value. In addition, energy use analysis was done by normalizing consumption with the outdoor temperature and the effect. Currently, building operation service is using energy signature curves normalized by the outdoor temperature to detect possible faults. Therefore, it is important to check if these curves can be implemented in this case as well.

Regardless of the above findings, after a year of use, the building achieved 3% lower energy consumption than calculated. Calculated and measured energy consumptions are shown in Fig. 5 and 6 respectively. Calculation of energy consumption was done according to NS 3031 [33].

Fig. 5. Calculated energy consumption for the case building

Fig. 6. Measured energy consumption for the case building

This decrease in the energy consumption, from comparison between Fig. 5 and 6, was due to better utilization of the heat pump and cooling plants. Cooling plants are integrated into the energy central. In the design there were no data on size and work principle of the energy central as shown by the low number of performances in Table 6. However, after some months of maintaining the building, the operation service developed a strategy how this system should be controlled. In addition, the current building electricity consumption is 78.9% of total energy consumption as shown in Fig. 7, while it was calculated to be 91%.

Fig. 7. Measured total energy use for the case building

To analyze the building energy use, electricity and district heating consumptions were monitored as shown in Fig. 8. Since cooling plants are using electricity, their electricity consumptions were monitored. In the case of the district heating, there are two measurements for the heating and domestic hot tap water. The measurements in the further text are weekly energy consumption.

Fig. 8. Measurement of energy flow

The electricity consumption and its peak in power normalized by the outdoor temperature are shown in Fig. 9. The electricity consumption normalized by the power is shown in Fig. 10. The peak in power is the peak noted in observed week. The data normalization was done to find influencing factors on the energy use.

Fig. 9. Electricity consumption normalized by the outdoor temperature

Fig. 9 shows that neither electricity consumption nor power is influenced by the outdoor temperature. There are two points for the peak in power (at December 10th, 2008 and February 19th, 2009) that are distinguished from the other points. By checking the hourly reports, it was found out that these peaks appeared due to interruption in the electricity supply. In addition, by checking hourly reports for different weeks, it was found out the hourly electricity consumption on working days oscillated between 180 and 540 kWh regardless of the outdoor temperature. Therefore, in this case the electricity consumption could not be related to the outdoor temperature.

Fig. 10. Electricity consumption normalized by the power

Fig. 10 shows that the electricity consumption can be related to the peak in power, if the two interruption points are omitted. A linear interpolation model between the electricity consumption and power has mean percentage error of 0.5%. This means, if the peak in power is higher, the electricity consumption is higher. Therefore, energy-efficiency measures should aim to decrease use of electrical appliances, so that the total electricity consumption can be decreased.

Fig. 11 shows both the heating consumption and its peak normalized by the outdoor temperature. There was only one point for the peak in effect at December 10th, 2008 that is distinguished from the other points. This high peak happened due to interruption in the heating supply. Since this interruption happened at the same time as the interruption for the electricity, this can be explained that a shut-off of the pump in the heating system induced interruption of the heating supply.

Fig. 11. Heating consumption normalized by the outdoor temperature

In contrast to the electricity consumption, heating consumption *can* be related to the outdoor temperature. To show this relationship energy signature curve for the weekly heating consumption is plotted in Fig. 12. The energy signature curve is provided by the linear interpolation of the consumption as a function of the outdoor temperature.

Fig. 12. Energy signature curve for the heating consumption

Fig.12 shows that it was not possible to establish a unique energy signature curve for the entire range of the outdoor temperatures from -2^{o}C to 16^{o}C. There is a break in the curve at 10^{o}C outdoor temperature. This break can be explained by the used equipment for heating. Under lower outdoor temperatures, all the systems (320.011, 320.012, 320.013, 360.010, 360.011, 360.012, and 313.010) in Figure 2 are in use. Under higher outdoor temperatures, the ventilation systems, 360.010, 360.011, and 360.012, can provide heating energy from the exhaust air and they do not need additional heating from the district heating system. The total installed capacity of the additional heat exchangers, which are labeled by LV03 in Figure 2, is 1046 kW according to the documentation. The installed capacity of the heating equipment is 210 kW according to the assembling drawings. The consequence of this significant difference in the installed capacity is the break in the energy signature curve. Therefore, when the peak heating effect is 200 kW at 10^{o}C outdoor temperature in Fig. 11, there is a break in the signature curve of Fig. 12. Since this difference in the heating capacity influences the signature curve, it is not possible to use a unique signature curve over a wide range of outdoor temperatures. There is a need to use a modified signature curve that represents different equipment characteristics as shown in Fig. 12.

Electricity consumption of the cooling plants can be related neither to the outdoor temperature nor to the peak in power. This means that the electricity consumption of the cooling plants is determined by building users.

Discussion

Mapping of the standards related to the LTC showed that the ventilation system performances are better defined by the standards than the other systems. For the ventilation system, 58% of the relevant performances can be found at the different levels of the building lifetime as shown in Table 3. Testing of the Norwegian LTC procedures showed that 36% of the defined ventilation performances can be monitored by BEMS, while 60% of the performances can be found in the producer technical guides as shown in Table 6. This means that the documentation and monitoring of the ventilation system is better than the other systems. The domestic hot water system, fan-coil system, and cooling system are poorly defined by both the standards and the building documentation in the case building. Even though there is no clear reason for better documentation of the ventilation system, it can be stated that higher requirements defined by standards induce better system documentation and monitoring.

Based on the reviewed standards related to the LTC in Section 3, there are four items that are missing for monitoring of energy performances: generic definition of performances, definition of improvements related to building performances, measurements in hydraulic system, and baseline values for energy-efficiency estimation. In the reviewed standards, there is not always a generic definition of the building performances, as mentioned in Section 3, for the performance requirements and energy-efficiency measures.

In addition, it is necessary to describe the improvement related to the energy performances to enable monitoring and documentation of a suggested energy-efficiency measure. The generic framework can encourage information exchange between different standards. Therefore, as an aid in developing generic framework EN ISO 16484, Building automation and control systems (BACS), Part 3: Functions [34], and EN 15603 [26] can be used.

Since in most of the HVAC installations, water is a medium for energy transfer, performances of hydraulic system are crucial for the performance of the entire system. Especially nowadays, when there is a huge use of frequency controlled pumps, dynamic pressure balance valves, and constant pressure control valves. However, review of the relevant standards and test of the LTC procedures showed poor definition of the hydraulic performances.

To estimate benefit of an energy-efficiency measure, it is necessary to have a common way for expressing energy baselines. In ASHRAE guideline 14 [35] for estimation of energy savings, there is suggestion that the values before the retrofit should be used as a baseline. In most of the reviewed European standards, the baseline should be design data. However, there is still a problem if different baselines are giving comparable results.

Conclusion

The paper presents Norwegian LTC procedures that enable tracking and quality control of the building performances during the building lifetime. The performance tracking is enabled by establishing a generic framework on building performances. The LTC procedures were tested on a case building and the amount of available data were presented. The same generic framework on the performances was implemented to review the standards related to the lifetime commissioning. In that way it was possible to estimate the amount of performances defined by standards.

In the suggested framework on the building performances, the prescriptive standard NS 3451 is used to start performance definition. As noted in [20], prescriptive standards state the required properties of an entity. Therefore, available national prescriptive standards should be used to define framework for the Cx work, because such national standards are usually well known among practitioners. Since LTC has been recognized as a quality control tool, standards developed to support EPBD were found relevant for LTC. In that way, if the LTC provides control on the building performances, an inspection report could be issued immediately upon request.

The results on the case building showed five findings due to that the Cx work did not start early in the design phase. These five findings can be explained as: two lacks in documentation, system over sizing due to lack of information, poor functional definition, and poor functional integration. Further, the test results of the framework on the performances showed that 20% of all the defined building performances can be monitored by BEMS. Even though 59% of all the defined performances can be found in the different documents; there are only 10% of common performances among different documents and building phases. This means that there was no generic performance definition in the building documentation. Regardless of the noted issues, the building achieved 3% lower energy consumption than calculated due to better utilization of the heat pump and cooling plants.

Since building information loss induces performance degradation, LTC procedures are necessary to be a knowledge-based tool that can enhance collection of building performance. To enable building data collection, it is necessary to develop a generic framework on building performances. In that way, such procedures give possibilities that building extension is enabled and any system change during the building lifetime can be easily noted.

Acknowledgements

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Table 1

Table 1. Mapping the Norwegian LTC procedures into the building lifecycle

Part 1 Framework for the commissioning project	Design	Construction	Operation
Requirements	**Part 2** Performance requirements in the design phase	**Part 3** Performance requirements in the construction phase	**Part 4** Performance requirements 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 2

Table 2. Performances of Radiator branch - South

320.012 Radiator branch - South	Performance	Performance name	Measurement	Unit	Value in design phase	Value in construction	Balancing
SB 40, Control valve	Water flow rate	320.012.VM40		m^3/h	8		
	Opening	320.012.OP40	434.005	%			
JP 40, Pump	Water flow rate	320.012.VM40		m^3/h	8	20.88	
	Pressure difference	320.012.TD40		Pa			
	Pressure after pump	320.012.TP40		Pa			
	Pump speed	320.012.PH40		^{o}/min		4600	
	Pump power	320.012.JP-E40		kW		0.45	
	Proportional control parameter	320.012.RPP40	434.005	-			
	Integral control parameter	320.012.RPI40	434.005	-			
	Differential control parameter	320.012.RPD40		-			
	Operation time	320.012.DT01		h			
SV 40, Balancing valve	Water flow rate	320.012.VM40		m^3/h			7.704
	Position	320.012.SV-P40		-			
	K_{VS}	320.012.SV-KV40		(m^3/h)/bar		33	
General functions	Supply temperature	320.012.T40	434.005/RT40	^{o}C			
	Return temperature	320.012.T41	434.005/RT41	^{o}C			
	Water flow rate	320.012.VM40		m^3/h	8.4		
	Heating power	320.012.E40		kW		104.58	

Table 3

Table 3. Mapping the relevant standards to the ventilation system

Performance	Requirement	Inspection	Measurement	Monitoring
Air change	EN 13779	EN 15239	ISO 12569	EN 15232
Humidity	EN 13779	EN 15239	EN 12599	EN 15232
Air flow extracted	EN 13779	EN 15239	EN 12599	
Air flow supplied	EN 13779	EN 15239	EN 12599	
Fan power		EN 15239	EN 12599	
Pressere rise across the fan			EN 12599	
Specific fan power	EN 13779	EN 15239		
Fan frequency			EN 12599	
Pressure before unit		EN 15239		EN 15232
Pressure after unit		EN 15239		EN 15232
Air flow before/after heat exchanger			EN 12599	EN 15232
Air temp. before/after heat exchanger			EN 12599	EN 15232

Table 4

Table 4. Mapping the relevant standards to the air-conditioning system

Performance	Requirement	Inspection	Measurement	Monitoring
Condensing pressure		EN 15240		
Cooling load estimated		EN 15240		EN 15232
Operation mode		EN 15240		EN 15232
Total air volume		EN 15240		
Running time		EN 15240		EN 15232
Specific fan power		EN 15240		
Pressure drop on water side		EN 15240		EN 15232
Water temperatures		EN 15240		
Storage tank volume		EN 15240		
Indoor air temperature				EN 15232
Outdoor temperature compensation				EN 15232

Table 5

Table 5. Mapping the relevant standards to boilers and heating systems

Performance	Requirement	Inspection	Measurement	Monitoring
Fuel consumption		EN 15378	EN 15378	
Operation hours		EN 15378		EN 15232
Boiler combustion power		EN 15378	EN 15378	
Combustion efficiency		EN 15378	EN 15378	
Circulation pump max. rated power		EN 15378		EN 15232
Pressure drop on water side				EN 15232
Unbalancing symptoms		EN 15378		EN 15232
Circulation pump set power		EN 15378		
Indoor temperature		EN 15378		EN 15232
Occupancy				EN 15232

Table 6

Table 6. Number of building functions

System	Purpose	Number of					
		Components	LTC functions	Design functions	Installed functions	BEMS functions	Common functions
313.010	Domestic hot water	6	32	11	0	2	0
320.010	Heating supply system	8	27	2	7	7	1
320.011	Heating branch - North	3	18	3	5	5	1
320.012	Heating branch - South	3	18	3	5	5	1
320.013	Heating branch - Atrium	3	18	3	5	5	1
350.010	Cooling system central	71	383	54	0	83	2
350.011	Cooling system supply	5	30	8	7	6	5
350.012	Fan-coil system	45	210	45	0	0	0
350.013	Fan-coil for IT room 1	3	14	3	0	0	0
350.014	Fan-coil for IT room 2	3	14	3	0	0	0
360.010	Ventilation system - South	19	87	23	52	31	30
360.011	Ventilation system - North	19	87	26	52	31	31
360.012	Ventilation system - East	19	87	26	52	31	34
	Total	208	1025	210	185	206	106

Figure 1

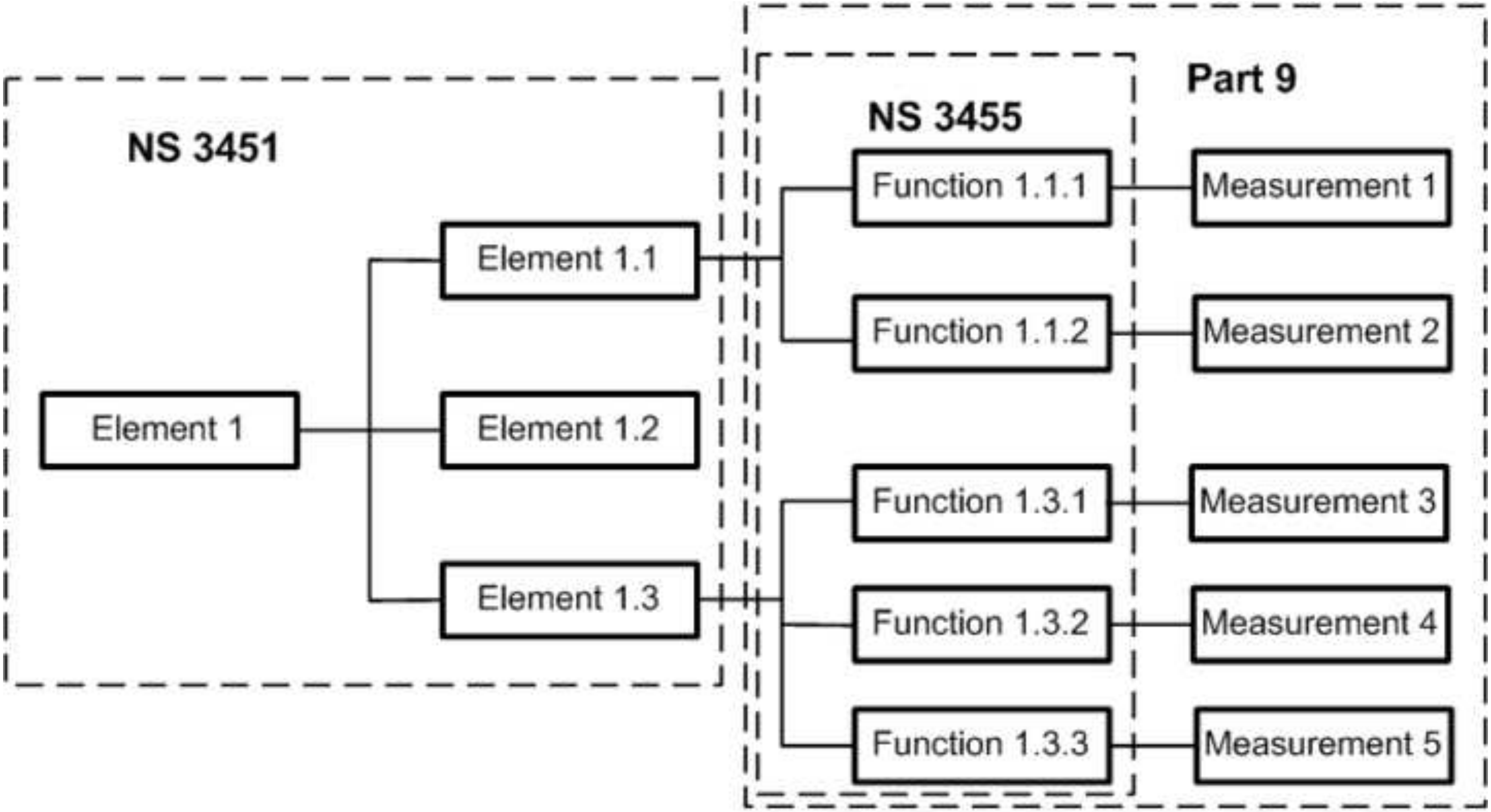

NS 3451
Element 1
Element 1.1
Element 1.2
Element 1.3
NS 3455
Function 1.1.1
Function 1.1.2
Function 1.3.1
Function 1.3.2
Function 1.3.3
Part 9
Measurement 1
Measurement 2
Measurement 3
Measurement 4
Measurement 5

Figure 2

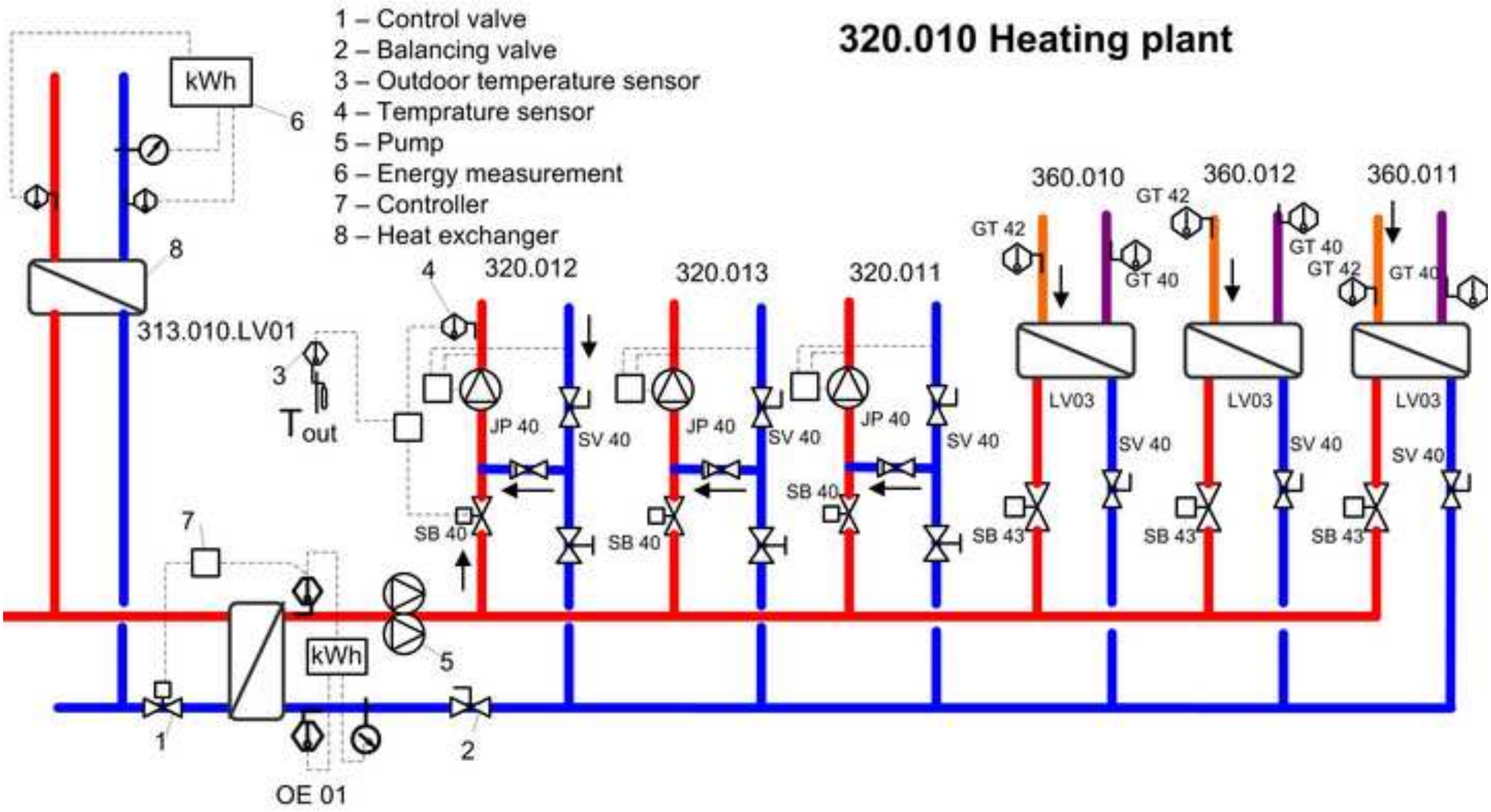
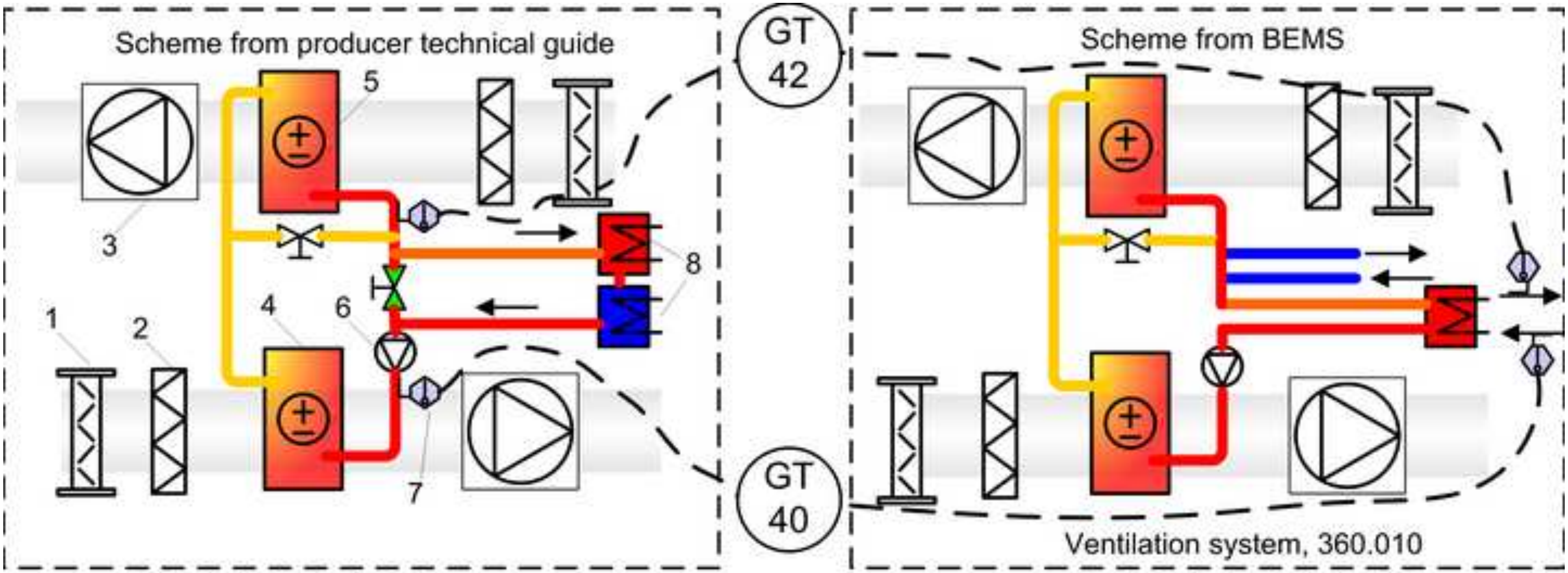

1 – Control valve
2 – Balancing valve
3 – Outdoor temperature sensor
4 – Temprature sensor
5 – Pump
6 – Energy measurement
7 – Controller
8 – Heat exchanger
320.010 Heating plant
kWh
6
8
313.010.LV01
3
Tout
4
320.012
320.013
320.011
360.010
360.012
360.011
GT 42
GT 40
JP 40
SV 40
SB 40
SB 43
LV03
7
kWh
5
1
2
OE 01

Figure 3

Figure 4



1 – Damper
2 – Filter
3 – Fan
4 – Heating/Cooling coil
5 – Heating/Cooling coil
6 – Pump
7 – Temperature sensor
8 – Heat exchanger

Figure 5

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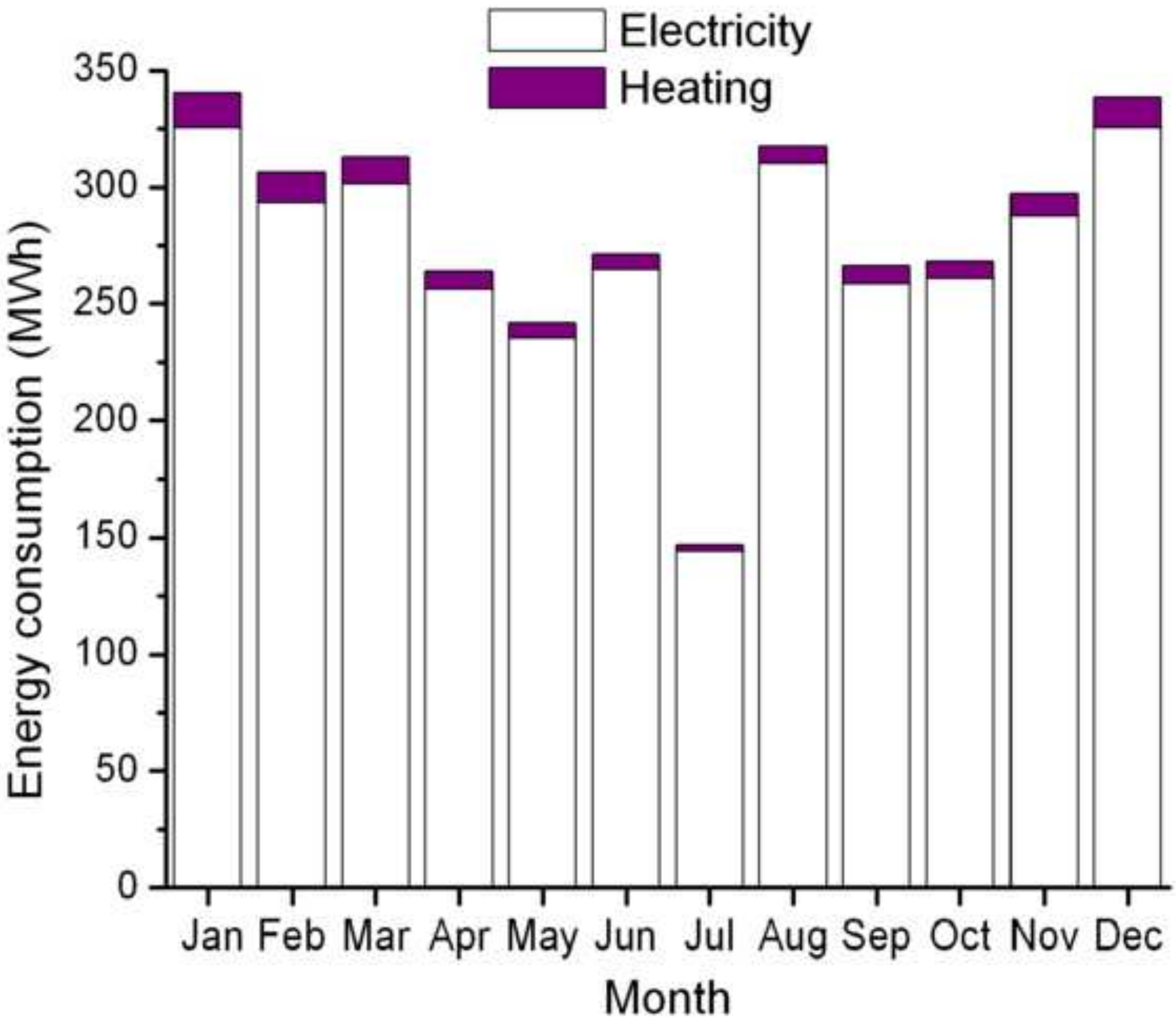

Figure 6
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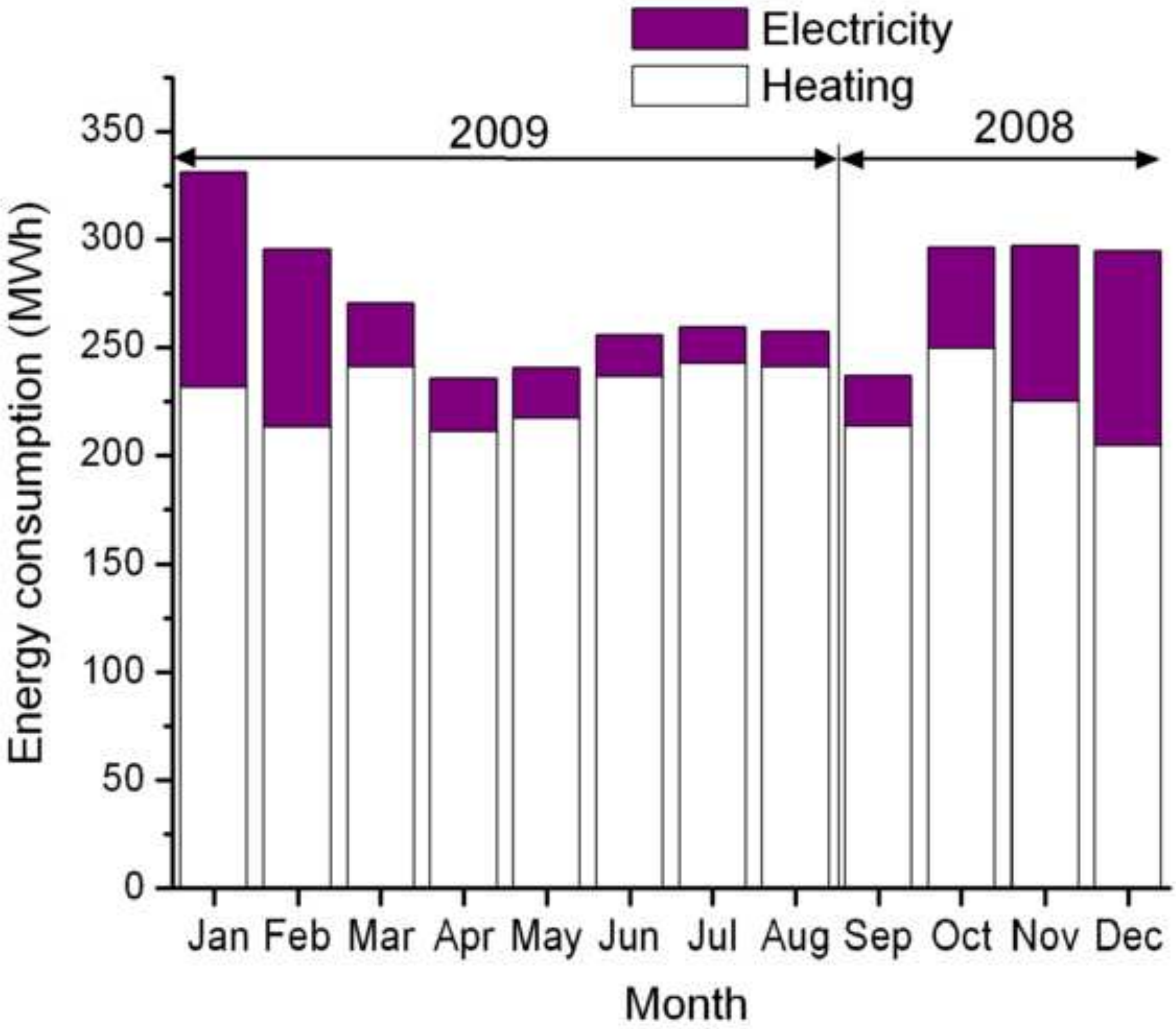

Figure 7

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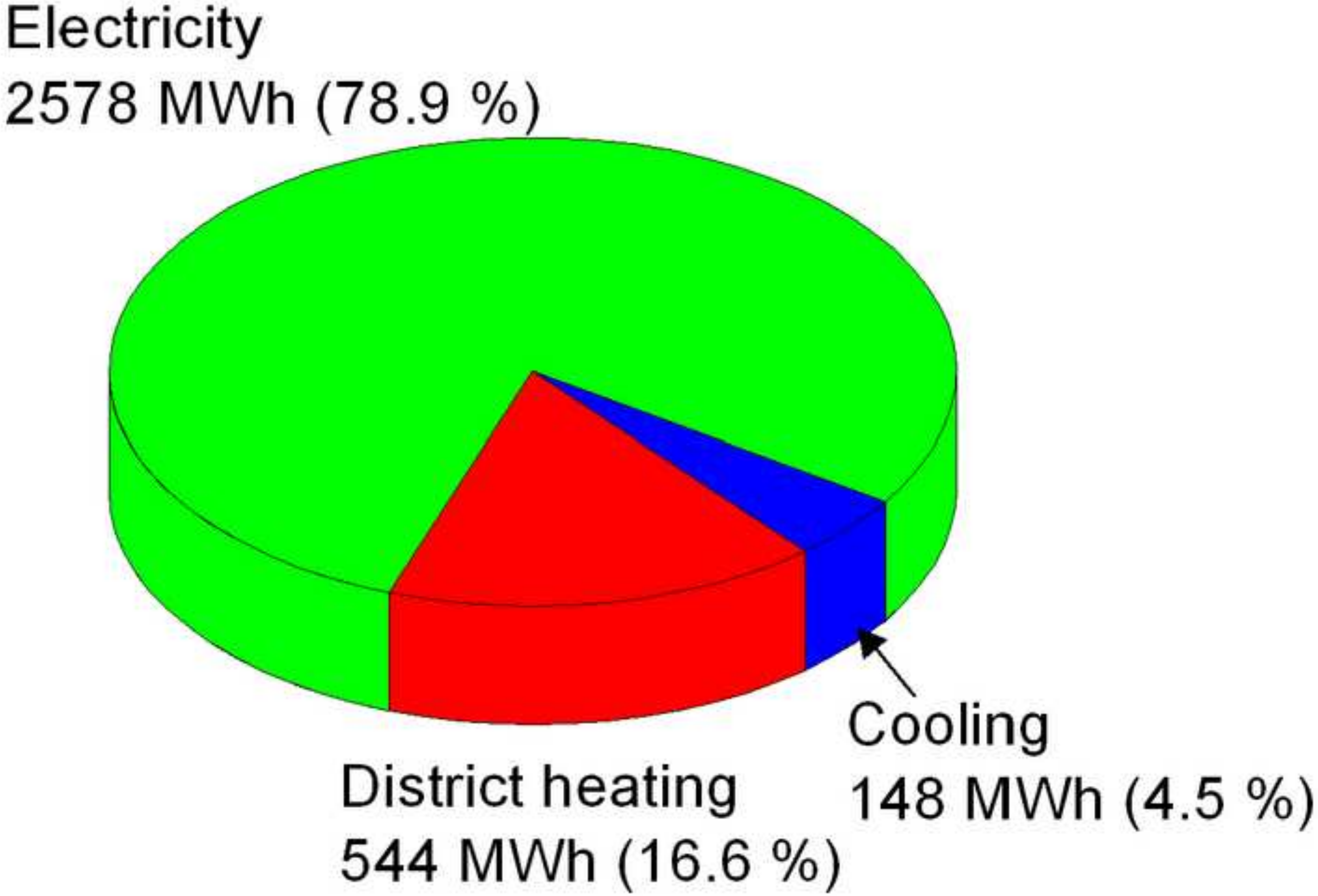

Figure 8

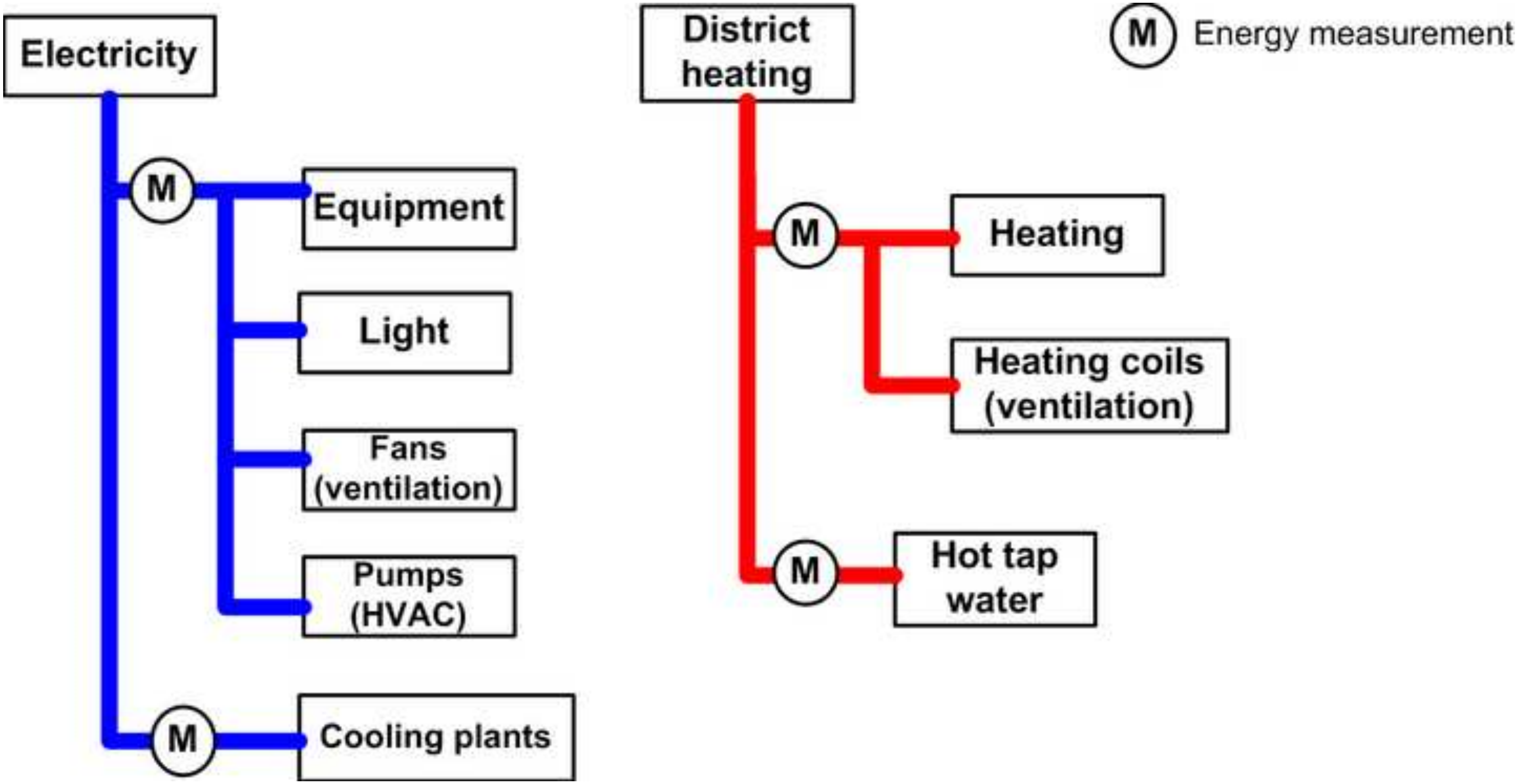
Electricity
M
Equipment
Light
Fans (ventilation)
Pumps (HVAC)
M
Cooling plants
District heating
M
Heating
Heating coils (ventilation)
M
Hot tap water
M Energy measurement

Figure 9

Click here to download high resolution image

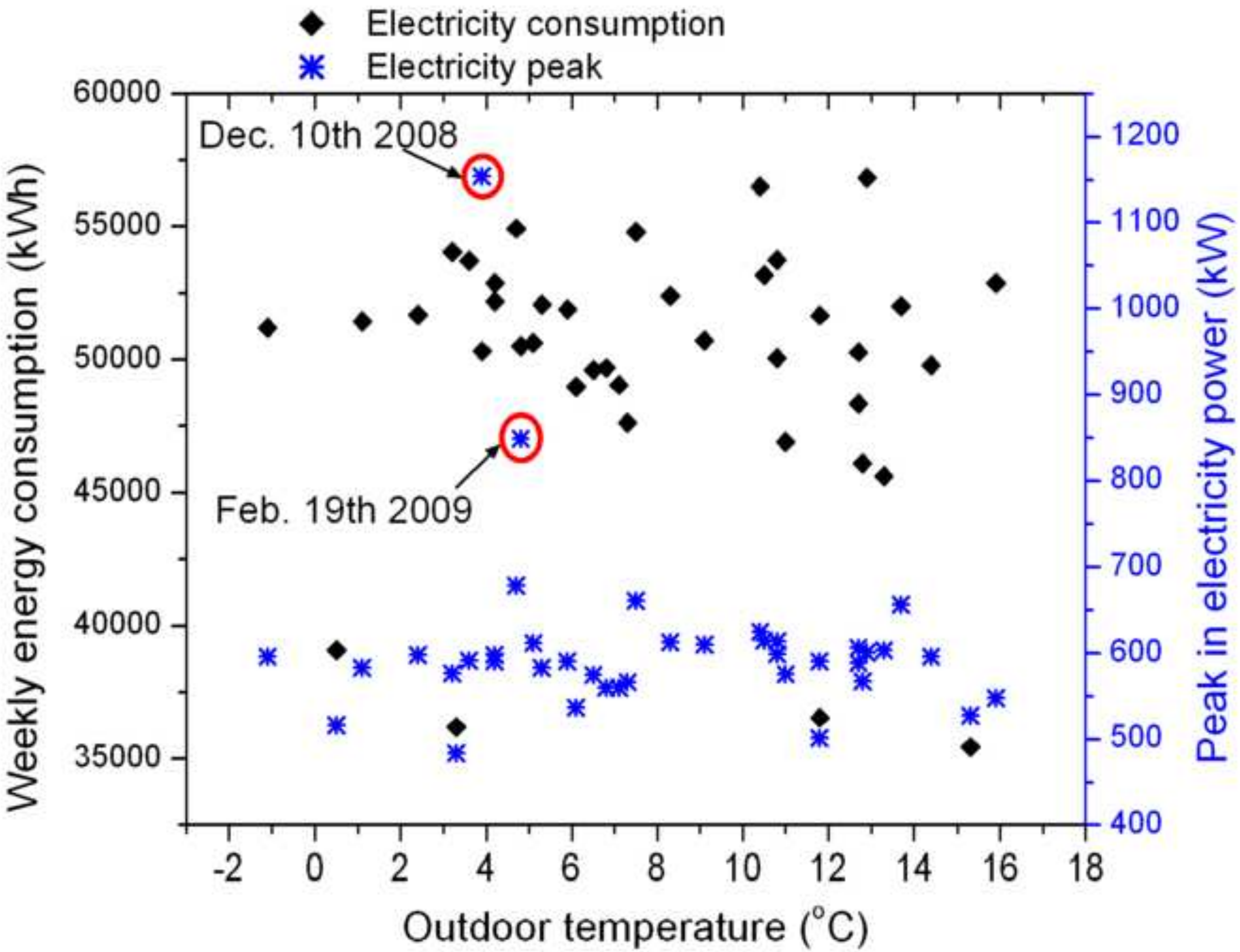

Figure 10

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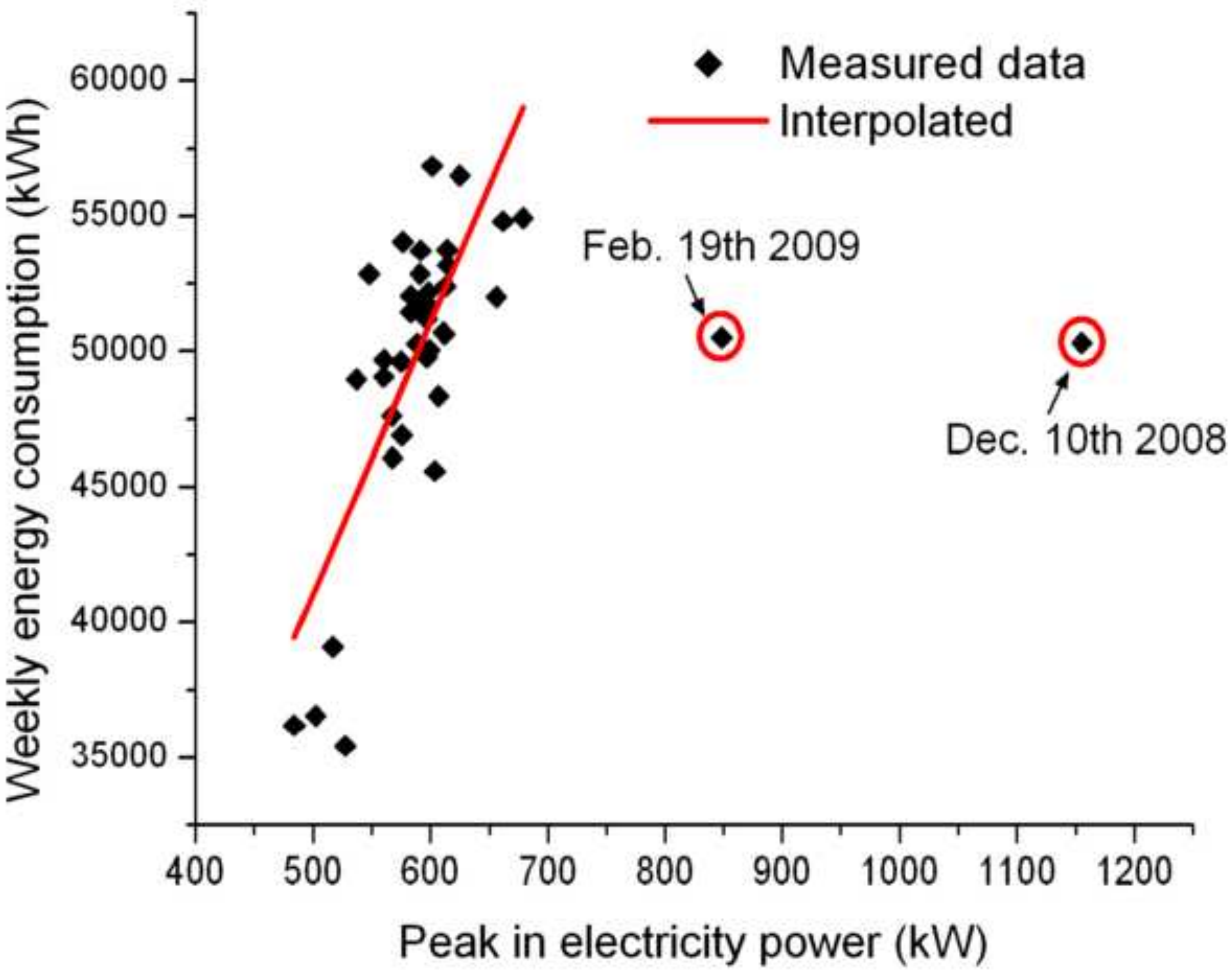

Figure 11

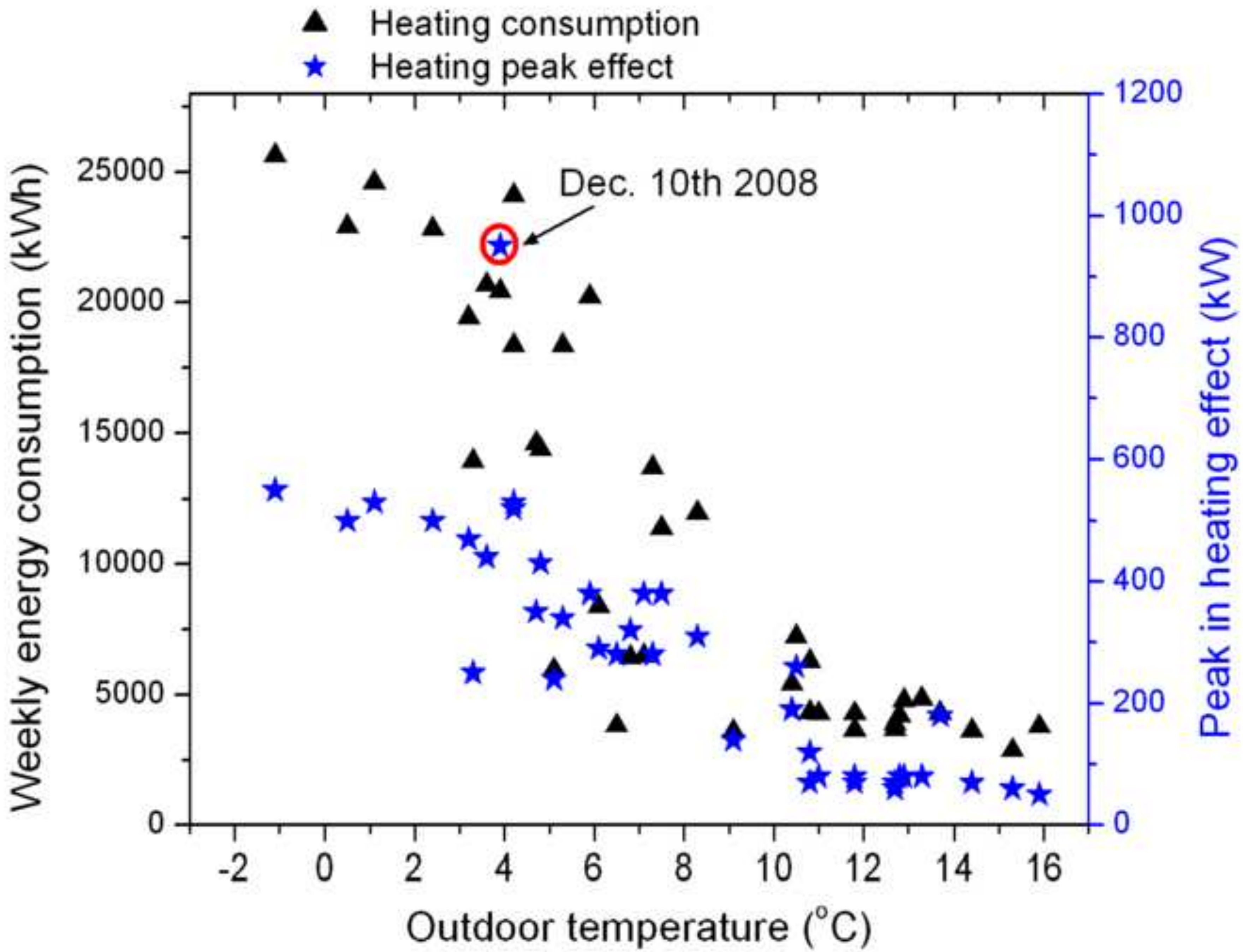
▲ Heating consumption
★ Heating peak effect
Dec. 10th 2008
Weekly energy consumption (kWh)
0
5000
10000
15000
20000
25000
Peak in heating effect (kW)
0
200
400
600
800
1000
1200
-2
0
2
4
6
8
10
12
14
16
Outdoor temperature (°C)

Figure 12

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