DANISH TECHNOLOGICAL INSTITUTE

Characterization and optimized control by means of multiparameter controllers

Technological Institute
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Preface

The report finalize the project "Characterization and optimized control by means of multi-parameter controllers" project no. 339-032 journal no. 464-06 financed by ELFOR.

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Projekt baggrund

Der er i de seneste år bygget mange kontorbygninger med store glasarealer i Danmark.

Erfaringer med disse byggerier er nu så mange, at der tegner sig et fælleds billede af fordele og ulemper ved denne type byggerier. Særligt er der nogle udfordringer med energiforbrug og indeklima.

Teknologisk Institut er et naturligt centrum for opsamling af denne viden, og instituttet har set et behov for at udføre en analyse af funktionerne forbundet med energiforbrug og indeklima i disse bygninger. Ved anvendelse af CTS anlæggene i disse bygninger, har man en unik mulighed for at udføre en avanceret analyse af indeklimaet og energiforbruget.

I forbindelse med projektet, dannede Teknologisk Institut en projektgruppe bestående af repræsentanter fra følgende virksomheder/institutter:

BusinessMinds
IMM, DTU
DTU-ICIEE
Teknologisk Institut
Dan-Ejendomme as

Dan-Ejendomme as blev som bruger i et glashus udvalgt til at være projektets tovholdere. "Teknikkerne" har udført selve forskningsprojektet og udarbejdet nærværende rapport, som indeholder en beskrivelse af analysemetoderne og analysens resultater.

Som både lejer i et glashus og som administrations- og driftsselskab - med en rådgivende projektafdeling - er Dan-Ejendomme as velplaceret til at være tovholder for projektet og til at skabe kontakter til andre ejere af glashuse.

Via projektet har Dan-Ejendomme as fået et unikt indblik i de problematikker, som kan være forbundet med glashuse. De erfaringer, der er opnået, er allerede ved at blive udnyttet af andre bygningsejere.

Projekt – sammenfatning og resultater set med brugerøjne

Tuborg Boulevard 12 i Hellerup er et ca. 7 år gammelt glaskontorkompleks udstyret med TAC's CTS-anlæg. Bygningen er ejet af PKA og huser tre lejere. Dan-Ejendomme as er den ene lejer og varetager samtidig driften af ejendommen. Flere af husets brugere har registreret en mindre tilfredshed med hensyn til indeklimaet, som har været en af grundene til, at projektet blev igangsat.

I projektet er der foretaget en detaljeret gennemgang af alle teknikkomponenter, der er indbygget i ejendommens varme-, køle- og ventilationsanlæg, og der er logget data fra CTS anlægget hvert 5. minut i mere end et år i 975 punkter.

Der er foretaget 2 indeklimaundersøgelser samt en avanceret undersøgelse af de loggede data.

Målet var at undersøge muligheden for at udvikle mere avancerede styringsværktøjer for installationerne med henblik på at nedbringe energiforbruget og på at optimere indeklimaet.

Med fundament i projektet har Dan-Ejendomme as suppleret projektets formål med at engagere teknikkerne, der har deltaget i forskningsprojektet, til at bruge deres viden i praksis. Resultatet af dette er en strategi for energioptimering af bygningen (se appendiks 8).

Det forventes, at der vil blive sparet mere end 30% på energiforbruget, og indeklimaet vil blive forbedret væsentligt alene ved at ændre på styringsstrategien i CTS-anlægget og ved nogle få ændringer i installationerne.

Udbedringerne er igangsat på Tuborg Boulevard 12.

Dette har alene været muligt på grund af den store viden om driftssituationen, der er fundet i nærværende projekt.

Der er straks taget tiltag til, at den viden, der er opnået, også benyttes i andre bygninger. Det forventes, at der ikke er behov for en lige så massiv undersøgelse af driftsdata, da der nu er en generel viden om en nødvendig driftsstrategi i bygninger af denne type.

Dan-Ejendomme as' erfaringer som deltager i forskningsprojektet og erfaringer fra flere tilsvarende bygninger

Problemstilling

- Selv efter 5 års gennemgangen kan der fortsat konstateres mange fejl på installationerne. Dette også selvom der løbende er brugt mange midler til fejlsøgning og -retning.
- Konstateret højt energiforbrug og dårligt indeklima.
- Manglende strategi eller måske en forfejlet strategi i software-løsningen for styring af de mange forskellige installationer er en væsentlig årsag til problemerne (fra første streg slås til bygningen er taget i brug)
- Uhensigtsmæssigt valg af komponenter og deres placering
- Manglende erfaring hos rådgivere og entreprenører.
- For lidt fokus fra de involveredes side til at sikre sig, at de udfordringer, der er ved glashuse, tilgodeses.

Forslag til forbedring

- Valg af hensigtsmæssige komponenter som for eksempel følere og deres placering kan efterfølgende give mulighed for et godt indeklima og en god anvendelse af tilført energi.
- Valg af styringsstrategi, der tager hensyn til energiforbrug og indeklima, og som kræver en helhedsvurdering af både software og komponenter, er essentiel. Dette kræver, at der tilknyttes en specialist, der har ovennævnte som hovedopgave.
- Afleveringen af projekter, hvor alle komponenter er dokumenteret, gennemprøvet, og hvor det også er tjekket, at der er en sammenhæng mellem softwarestyring og kompo-

nenter. Dette er en proces, der løber frem til f.eks. 1, 2 eller 5 år efter bygningens ibrugtagning.

- Logning af CTS punkter løbende i en periode på 6 måneder med fx 10 min intervaller, der kan bruges til en eventuel analyse. Værktøjerne er nu udviklet.
- Arbejde med udvikling af konceptet Multiparameter Controllere som kan ske i step.

Forventede resultater

- Store energibesparelser (mere end 30%) og et meget bedre indeklima (brugertilfredshed).
- Efteruddannelse af rådgivere og entreprenører er nu mulig med baggrund i de problemstillinger, der er fundet i denne type bygninger.
- Der er fundet nye måder at logge, lagre og behandle store datamængder med henblik på ovennævnte analyse af karakteristika ved bygninger med CTS-anlæg.

Dansk resume

Dårligt indeklima og høje energiomkostninger i kontorbyggeri koster årligt det danske samfund milliarder af kroner. Det anslås, at dårligt fungerende bygninger og installationer årligt har meromkostninger på omkring 10 milliarder som følge af forøgede drift- og vedligeholdelsesomkostninger – herunder specielt forøget energiforbrug. Det ofte dårlige indeklima vurderes at lede til et årligt tab på omkring 30 milliarder som følge af forringet effektivitet og sygefravær.

Der er mange grunde til at danske kontorbygninger ikke drives optimalt – f.eks.: installationerne er dimensioneret forkert, der er fejl i installationerne, installationerne er idriftsat forkert, brugen af bygningen er ændret, installationerne er dårligt vedligeholdt, der er begrænsede styringsmuligheder, og ofte har driftspersonalet ikke tilstrækkelig viden om installationerne til at drive bygningen korrekt bl.a. på grund af dårligt dokumenterede installationer. Hertil kommer at mange nyere kontorbyggerier har store glasfacader uden tilstrækkelig solafskærmning med deraf følgende overophedningsproblemer.

Til at styre bygningerne er der ofte installeret en eller anden form for CTS-anlæg (Central Tilstandskontrol og Styring). Disse er dog ofte karakteriseret ved, at de enkelte subsystemer styres separat, at der ikke tages hensyn til dynamikken i bygningen, at sensor-signaler ofte kun anvendes til at styre f.eks. én ventil, og at der ikke logges data, som kan anvendes til senere fejlfinding. Men i dag er computerkraft og lagring af data blevet så billigt, at det er muligt at udvikle væsentlig mere avancerede styringsmuligheder og at logge alle data (både sensor- og aktuatorsignaler) i systemet med en høj frekvens.

Formålet med nærværende projekt har været at undersøge, hvordan det er muligt at udnytte de store datamængder, der sendes rundt i et CTS-anlæg mere optimalt. I projektet er der fokuseret på tre områder: a) dataopsamling og –håndtering, b) diagnosticering og c) multiparameter-sensorer(controllere). Desuden er der gennemført en detaljeret undersøgelser af indeklimaet i bygningen. Der er taget udgangspunkt i en kontorbygning i Tuborg havn – bygning og installationer er beskrevet detaljeret i kapitel 2. Bygningen, der er på fem etager plus kælder, har et opvarmet etageareal på 21.199 m² og blev ibrugtaget i maj 2002. Bygningen har et centralt atrium med et areal på 1.182 m². Bygningen har store glasfacader. Der er klager over indeklimaet i bygningen, og energiforbruget er højere end forventet.

Dataopsamling og -behandling

Et af formålene med projektet var at undersøge, hvor meget information det er muligt at trække ud af et traditionelt CTS-anlæg uden at tilføje ekstra sensorer eller funktionalitet til anlægget. Dog blev der installeret CO_2- og fugtsensorer i afkastet i de tre hovedventilationsanlæg.

Der blev i alt logget 975 værdier i CTS-anlægget – de fleste hvert 5. minut og et par enkelte som 10 minutters værdier. De loggede værdier er detaljeret beskrevet i afsnit 3.1. Dataene er opdelt i følgende hovedgrupper: vejrdata, opvarmningssystem, ventilationssystemer, kølesystemer, kontorer og atrium. Størstedelen af dataene er temperaturer i kontorer og installationer – både ønskede værdier (sætpunkter) og faktiske værdier (målte værdier). Men også ventilstillinger, hastighed af ventilatorer, købt fjernvarme, el til køleanlæg, mm. er blevet logget.

CTS-anlægget i bygningen var ikke forberedt for logning af data. Til trods for dette er det lykkedes at få overført data fra størstedelen af perioden på 14 måneder og fra de fleste målepunkter, selv om overførslen af data skete manuelt.

Desuden er der fra DONG Energy blevet overført timeværdier for elforbrug i bygningen – både det samlede elforbrug til bygningens installationer samt til de tre firmaer, der bebor bygningen inkl. til køkkenet.

I forbindelse med de detaljerede indeklimamålinger er der i to perioder blevet opsat separate dataloggere 17 forskellige steder i bygningen. Disse dataloggere loggede hvert femte minut lufttemperatur, relativ luftfugtighed, lysforhold og CO_2. Desuden er der gennemført to elektroniske spørgeskemaundersøgelser vedr. folks oplevelse af indeklimaet.

Logningen af data stod på i 14 måneder fra 1. juli 2007 til 31. august 2008. Det var således en meget stor mængde data, der blev logget – data der oven i købet var logget med forskellige tidsskridt. Der var derfor brug for at lagre dataene på en sådan måde, at det er let for forskellige applikationer at få fat i de ønskede data inkl. alle medfølgende informationer som tidsstempling, sensor navn, placering, mm. Til dette blev valgt databasesystemet MySQL, fordi dette system giver mulighed for at behandle store datamængder på en effektiv møde. Desuden kan MySQL køre på mange forskellige platforme. Opbygningen af databasen er beskrevet detaljeret i afsnit 3.2.

Det var i første omgang meningen at visningen af data skulle ske ved hjælp af pivotdiagrammer i Excel. Men det viste sig at være for langsomt – på grund af den store datamængde men specielt når data med forskellige tidsskridt skulle vises. I stedet blev freewaret R valgt som platform for visning og behandling af de loggede data – dette er beskrevet detaljeret i Appendix 6 og 7. R blev kørt på en af serverne hos IMM, som projektets deltagere fik adgang til. R indeholder desuden en lang række statistiske muligheder som også har været anvendt i projektet i forbindelse med undersøgelse af multiparameter-sensorer.

Dataopsamlingen og –behandlingen var mere tidskrævende en forventet. Det var nødvendigt udvikle softwarerutiner til dette formål. Håndteringen af logningerne har givet følgende vigtige viden:

- logning og overførsel af data skal være automatisk
- der skal være et automatisk tjek af at alle valgte værdier bliver logget
- der skal være et automatisk tjek af, at sensorsignalerne varierer som forventet – at ingen sensorer f.eks. hænger
- der skal være tjek for outliers – dvs. værdier der ligger for langt væk fra andre værdier i en tidsserie. Disse skal dog ikke altid rettes automatisk, da de kan være udtryk for en reel tilstand og ikke nødvendigvis en ”fejlmåling”
- det skal være let grafisk at vise ønskede tidsserier og kondensater af tidsserier (f.eks. kumulative frekvenskurver og boksplot)

I projektet er der allerede blevet udviklet prototyper af software til behandling og visning af loggede tidsserier. Prototyper som kan anvendes som baggrund for udvikling af generelt software til behandling, tjek og visning af tidsserier.

Indeklima

Da der er mange klager over indeklimaet i bygningen, blev der gennemført en detaljeret undersøgelse af dette med specielle dataloggere 17 steder i bygningen samt elektroniske spørgeskemaer. Appendix 2.5 giver et udpluk af kommentarer fra spørgeskemaundersøgelserne. Som det ses, koncentrerer klagerne sig primært om for høje temperaturer, skiftende temperaturer, træk, luftkvalitet og støj.

Undersøgelsen viste (se kapitel 4), at specielt om vinteren er rumtemperaturen i bygningen højere end anbefalet. Målingerne viste også, at rumtemperaturen ikke varierer meget hen over året. De højeste temperaturer blev målt i de vestvendte kontorer, som samtidigt også har det relativt største vinduesareal i facaderne.

Appendix 4 viser, at rumtemperaturen varierer med 2 og 4 K over dagen.

CO_2-koncentrationen er lav, hvilket indikerer at volumenstrømmen i ventilationsanlæggene er høj i forhold til belastningen. Men samtidigt klager flere over dårlig luftkvalitet, hvilket kan tyde på, at der er andre forureningskilder end personer.

Ved hjælp af røg og håndholdt lufthastighedsføler blev det konstateret, at der kan forekomme træk ved skriveborde, der er placeret under (og mellem) to kølebafler, hvorfra den friske luft blæses ind under loftet – se figur 5.5.

Det anbefales at:

- at rumtemperaturen i bygningen kontrolleres bedre, så for høje temperaturer og for store fluktuationer udgås
- at trækgener fra indblæsningen af friskluft minimeres

Dianosticering

Et af formålene med projektet var at undersøge, hvordan adgangen til tidsserier kan forøge udbyttet af en traditionel inspektion af installationerne i en bygning. En traditionel inspektion har typisk det problem, at man kun kan undersøge driften af installationer i det tidsrum, man er i bygningen eller er logget ind på CTS-anlægget. Dvs. det er normalt et statisk billede, man får af driften af bygningen. Hvordan installationerne kører f.eks. om natten vides egentlig ikke, selvom man har adgang til sætpunkter og programmerede driftstider. Samspillet mellem forskellige installationer er også ofte vanskeligt at kortlægge uden tidsserier.

Resultatet af den visuelle gennemgang af tidsserierne vil kort blive beskrevet i det følgende. For en detaljeret beskrivelse henvises til kapitel 5. I det følgende er hovedresultater og forslag til ændringer fremhævet med fed og kursiv – andre mindre betydende forslag kan findes i de gule bokse i kapitel 5. Det skal dog pointeres, at en ændring ét sted vil influere på andre forhold. Derfor er forslagene ikke ”absolutte” men skal indgå i en trial and error proces, hvor effekten ved ændringer vurderes, hvilket sandsynligvis vil føre til justeringer af de foretagne ændringer.

En sammenligning af de 17 rumtemperaturer målt i forbindelse med de detaljerede indeklimamålinger og CTS-anlæggets temperaturfølere i de samme rum viste en forskel på ±2 K.

Dette er ikke overraskende, da CTS-anlæggets temperaturfølere er placeret på vægge, mens følerne for de detaljerede indeklimamålinger var placeret ude i rummet i nærheden af en arbejdsplads. En nærmere undersøgelse viste, at for visse af CTS-anlæggets følere faldt temperaturen drastisk i dagtimerne i forhold til indeklimamålingerne, mens de var meget ens om natten. Det viste sig, at disse (CTS) sensorer blev ramt af en kold luftstrøm fra kølebaflerne i loftet***. Undersøgelsen viser således, at CTS-anlæggets målte rumtemperatur ikke nødvendigvis er den rumtemperatur, som personerne i rummet føler.***

Som allerede nævnt viste røg og håndholdt lufthastighedsføler, at der er træk ved visse arbejdspladser. Specielt arbejdspladser der er placeret under (og mellem) to kølebafler og arbejdspladser placeret op mod en væg, hvor luften fra kølebaflerne rammer væggen og ledes ned mod arbejdspladsen. Undersøgelsen viste samtidigt, at kølebaflerne er meget uens indreguleret – sandsynligvis er nogle kølebafler blevet ændret på grund af klager. ***Da CO_2-koncentrationen og det relative fugtniveau er lavt i afkastluften fra kontorerne, bør det undersøges, om volumenstrømmen i ventilationsanlæggene kan reduceres for derved at reducere trækgenerne. Volumenstrømmen i anlæggene er allerede blevet reduceret til 75-80% af designgrundlaget, men en yderligere reduktion på 20% vurderes at være forsvarligt. Samtidigt skal volumenstrømmen gennem alle kølebafler indreguleres for dels at sikre høj ventilationseffektivitet i rummene dels at reducere trækgener.***

Der er generelt høje rumtemperaturer i bygningen specielt i den vestvendte del med store glaspartier i facaden, men også i andre rum uden stort solindfald er der overtemperaturer. En undersøgelse af elforbruget på de enkelte etager viser et standbyforbrug på op til 40-50% af forbruget om dagen. Dette er nok primært servere, der er tændt hele natten. ***Der bør gøres en indsats for at reducere standbyforbruget om natten, da dette er med til, at bygningen har en højere rumtemperatur om morgenen end nødvendigt – samt et højere elforbrug end nødvendigt.*** I dagtimerne er elforbruget 250 kW hvilket kun er 50% af designgrundlaget på 12 W/m² til pc'er og 15 W/m² til lys. Denne ændring i forhold til designgrundlaget skyldes, at mange af medarbejderne i de tre firmaer er konsulenter, der ofte ikke er på kontoret.

Ventilationsanlæggene er sat til at starte mellem kl. 4 og 6 om morgenen og slukkes igen kl. 20. ***Som følge af det lave CO_2- og fugtniveau bør der gøres forsøg med at ændre driftstiden – f.eks. til 8:00-16:00*** – hvis der ikke er behov for frikøling på grund af for høje rumtemperaturer i bygningen – se nedenfor.

Styringen af ventilationsanlæggene tillader frikøling med udeluft om natten, hvis der er overtemperaturer i bygningen. Rent praktisk betyder det, at ventilationsanlægget startes mellem 0:00 og 4:00 og sender udeluft direkte ind i bygningen – dvs. den roterende varmeveksler er ikke i funktion. Når ventilationsanlægget starter "rigtigt" mellem kl. 4 og 6, bliver sætpunktet for indblæsningstemperaturen den styrende parameter. I f.eks. figur 5.14 er denne sat til ca. 21°C. Det betyder, at den roterende varmeveksler bliver startet, og da det ikke altid er nok, bliver varmefladen med fjernvarme også startet op for at nå de 21°C – selvom rumtemperaturen i bygningen generelt er for høj. Derfor startes både køleanlægget, der leverer koldt vand til kølebaflerne, og køleanlægget, der betjener VAV-rummene (typisk møderum uden kølebafler). ***Det betyder, at der først bruges energi på at opvarme den friske luft, hvorefter der bruges energi på at nedkøle denne luft, fordi der er overophedningsproblemer i bygningen. Det er energispild. Der er derfor brug for en ændring i styringsstrategien for konditioneringen af den friske luft. I første omgang foreslås det at sænke fremløbstemperaturen på den friske luft til 16°C for at udnytte udeluftens frikølende evne. Desuden foreslås det at udvide frikølingen om natten, så rumtemperaturen om morgenen ikke overstiger 23°C.***

Der er to køleanlæg i bygningen: et til direkte køling i rummene via kølebafler (køleanlæg 2) og et til central køling af friskluften (køleanlæg 1) – det sidste er specielt til møderummene, der ikke har kølebafler. Målepunkterne i CTS-anlægget er ikke tilstrækkelig til en detaljeret evaluering af køleanlæggenes funktion, men ud fra de tilgængelige tidsserier kan det ses, at ***køleanlæg 1 typisk kører meget on/off drift med reduceret effektivitet til følge, mens køleanlæg 2 på grund af det store kølebehov i kontorerne kører mere jævnt. Den ovennævnte sænkning af frisklufttemperaturen til 16°C reducerer driftstiden for køleanlæg 1 og behovet for køling fra køleanlæg 2. Men derudover skal det sikres, at de to køleanlæg kører ved den højest mulige fremløbstemperatur til køleflader/kølebafler, da dette forøger anlæggenes effektivitet. Desuden bør det overvejers, om køleanlæg 1 kan kobles sammen med den indirekte frikøling, som allerede er etableret for køleanlæg 2, således at kølekompressorene kan slukkes, når udelufttemperaturen er tilstrækkelig lav til alene at producere den ønskede fremløbstemperatur til kølefladerne. Tidsserien for elforbruget til køleanlæg 1 viser, at der er et standbyforbrug på 0,8 kW, når dette anlæg ikke kører. Standbyforbruget bør findes og helst elimineres. Desuden bør der sættes frekvensregulering på pumper, der ikke allerede har dette.***

Tidsserierne viser, at mens der generelt er overophedning og fluktuerende rumtemperaturer i bygningen, så er atriet næsten perfekt reguleret - tæt omkring en rumtemperatur i opholdszonen på ca. 22°C. Et atrium opfattes ellers typisk som en cirkulationszone, hvor rumtemperaturen gerne må fluktuere både over døgnet og over året. Kølingen i atriet i sommerhalvåret er gratis, da det sker ved at åbne vinduer i taget og forneden langs atriets perimeter til det fri, men ***der kan spares energi ved at sænke temperaturen i fyringssæsonen – f.eks. til 20° (da der er spisepladser i atriet). For at sænke temperaturen og dermed varmetabet gennem loftet, foreslås det, at fremløbstemperaturen til ribberørene under taget sænkes og kun hæves i frokostpausen.***

Fremløbstemperaturen til radiatorkredsen følger en udetemperatur-korrigeret kurve, men stiger til 70°C, når blot én radiatorventil kalder på varme. ***Der bør implementeres en ny rutine for fastlæggelse af fremløbstemperaturen til radiatorkredsen, der reducerer den gennemsnitlige fremløbstemperatur uden at forringe komfortniveauet.***

På baggrund af ovenstående vurderes det, at der kan spares i størrelsesorden 50% af elforbruget til installationer (omkring 350.000 kWh) og i størrelsesordenen 25% af varmebehovet (omkring 300.000 kWh). Der er allerede på baggrund af projektets resultater blevet udarbejdet en strategi for energioptimeringen af bygningen (Olsen og Poulsen, 2010). Tiltagene vil blive implementeret i løbet af første halvår af 2010.

Multiparameter-sensorer(controllere)

Den detaljerede evaluering af indeklimaet og tidsserier har givet meget nyttig information om bygningen samt forslag til, hvordan styring og installationer kan ændres, så komforten i bygningen øges samtidigt med, at energiforbruget reduceres betragteligt. Men det er dyrt at gennemføre detaljerede indeklimamålinger og dyrt at have eksperter til at evaluere mange tidsserier. Derfor er der behov for automatisering af evalueringsgrundlaget og online optimering af styringen af bygning og installationer – dvs. multiparameter-sensorer og -controllere.

Fangers komfortligning er en form for multiparameter-sensor, hvor måling af rumtemperatur, strålings-assymetri, lufthastighed og luftfugtighed sammen med en antagelse om beklædnings- og aktivitetsniveau giver et mål for, hvor mange, der vil være utilfredse med det aktuelle indeklima. Altså en størrelse der ikke direkte kan måles – dvs. et virtuelt sensorsignal. Fangers komfortligning er fremkommet på baggrund af mange års forskning og laboratorieforsøg. Sådan en empirisk sammenhæng er det ikke muligt at opbygge for den undersøgte bygning med 975 loggede værdier. I stedet var det formålet at undersøge anvendelsen af avanceret statistik til at generere multiparameter-sensorer til karakterisering af den aktuelle driftstilstand af bygning og installationer. Hvis disse virtuelle sensorsignaler anvendes til styring af installationerne skabes multiparameter-controllere.

Som et trin på vejen mellem visuel inspektion af tidsserier og multiparameter-sensorer er kumulative frekvenskurver (afsnit 5.6) og boxplot (afsnit 6.2.2) blevet undersøgt. Her komprimeres f.eks. et helt års målinger af temperaturen i et rum i én figur som er relativ let at sammenligne med et ønsket udseende. Dette gør det lettere at spotte rum, som fungerer anderledes end gennemsnittet, men også at se, hvad der er galt. For begge metoder gælder dog, at der er behov for udvikling af det udseende, som de "målte" figurer skal sammenlignes med.

Værdien af multiparameter-sensorer er meget afhængig af det datasæt, som de genereres på baggrund af. Under afsnittet Dataopsamling og –behandlig er allerede nævnt nogle af de udfordringer, der var med de loggede værdier fra bygningen. Men der skal desuden tages hensyn til, at de loggede værdier har forskellig tidsstempel og tidsskridt. Projektet har vist, at det er en stor opgave at undersøge og behandle loggede data fra et større CTS-anlæg samt at bringe dem på en form, som er velegnet til generering af multiparameter-sensorer. De udviklede rutine i programmet R viser dog, at det er muligt at udvikle software, der muliggør en automatiseret håndtering og behandling af de store mængder loggede værdier. Udover udvikling af rutiner til datahåndtering, er der i projektet gennemført indledende undersøgelser af statistiske metoder til generering af multiparameter-sensorer. I første omgang er Principial komponent analyse blevet undersøgt – se kapitel 6. Principial komponent analyse er anvendt til at finde temperaturermålinger som afviger fra det tilsigtede og som derfor bl.a. afslører situationer hvor temperatursensorerne ikke er hensigtsmæssigt placeret. Det er også vist hvorledes principal komponentanalyse kan anvendes til at give signaler som er bedre velegnet til en egentlig kontrol/regulering, og dette vil ved implementering kunne give en langt mere robust regulering.

Af andre metoder, der anses som kandidater til generering af multiparameter-sensorer er:

- State space modeller
- Lineære differensligninger
- Energisignaturer - som er blevet undersøgt i projekter for Elsparefonden
- Dekomposition
- Lavpas og højpas filtrering
- Spektrum analyse

Der forestår stadig et stort arbejde i at nå fra logning af data fra CTS-anlæg til optimal styring via multiparameter-controllere. Men nærværende projekt har vist, at der findes mange værdifulde oplysninger om bygning og installationer gemt i disse data. Oplysninger som på den korte bane kan udnyttes til bedre indregulering af systemerne, men de helt store besparelser ligger i en online optimal styring af bygningerne, en styring der hele tiden tilpasser sig de givne forhold og den aktuelle brug af bygningen. Det er derfor nødvendigt at forsætte arbejdet omkring udvikling af multiparameter-sensorer og –controllere.

Generel anvendelse af projektets resultater

Projektet har vist, at det er muligt at indsamle og integrere de kolossale mængder af data, der skabes under drift af en større kontorbygning. Der er i projektet identificeret forskellige udfordringer i forhold til at sikre kvalitet og tilgængelighed af de indsamlede data, og der er udarbejdet anbefalinger til at imødegå disse i en driftssituation.

De matematiske analyser baseret på datamaterialet har bekræftet antagelsen om, at det er muligt at bruge avancerede statistiske metoder til at finde sammenhænge og diagnosticere aktuelle (styrings)tilstande. Dette er en forudsætning for og peger frem imod udviklingen af multiparameter-sensorer/controllere. Sådanne sensorer/controllere benyttes i dag til styring af andre former for komplekse systemer, men har ikke hidtil været benyttet i bygninger. Det er derfor et væsentligt resultat af projektet, at det er vist, at metoderne kan anvendes på denne form for datamateriale fra CTS-anlæg, og der er udviklet teknikker til at præparere data og diagnosticere forhold vedr. datakvalitet.

Projektet har også vist, at det er muligt at anvende visuel inspektion af data til en detaljeret evaluering af indeklimaet. Det har været muligt at gøre det meget omfattende datamateriale tilgængeligt på en form, som har kunnet understøtte en bygningsgennemgang og underbygge konklusioner om forskellige uhensigtsmæssige driftsforhold i bygningen. Disse resultater er principielt alene gyldige for den behandlede bygning. De kan derfor ikke direkte overføres til andre bygninger, da indeklima og styring af installationer kan være væsentlig forskellig fra den undersøgte bygning. Men det vurderes dog, at erfaringerne fra projektet kan være en inspirationskilde til at finde fejl og mangler i andre bygninger. Det vurderes, at det med nærværende rapport som udgangspunkt er muligt at gennemføre væsentlige besparelser i andre bygninger. Samtidigt vurderes det også, at besparelsespotentialet vil være væsentlig større, hvis der er adgang til tidsserier fra CTS-anlægget og disse benyttes i analysen.

Projektet har også været en inspirationskilde i det arbejde Teknologisk Institut af Erhvervs- og Byggestyrelsen blev bedt om at udføre i forbindelse med de kommende bygningsreglementer. Teknologisk Institut blev bedt om at gennemføre en udredning om installationer - herunder bygningsautomatik – til de kommende bygningsreglementer. I (Holk, 2008) bliver det således foreslået, at der i nye bygninger stilles krav om at logge på CTS-anlæg og at gemme data minimum et halvt år bagud. Der foreslås også krav til bl.a. samordnet idriftsætning, registrering af forbrug (også delforbrug), entreprisegrænser, kvalitetssikring, dokumentation, uddannelse, mm. for at sikre at installationer og styringen fungerer, når de bliver taget i brug.

1. Introduction

Poorly functioning HVAC systems (Heating, Ventilation and Air Conditioning), but also separate heating, ventilation and air conditioning systems are costing the Danish society billions of kroner every year: partly because of increased energy consumption and high operation and maintenance costs, but mainly due to reduced productivity and absence due to illness because of a poor indoor climate. It is estimated that the annual expenses are:

- approx. DKK 10bn in increased start-up, operational (including energy) and maintenance costs (The association DFM, 2002) (Akademisk Arkitektforening et al, 2004). The industry's own analyses show that most buildings and technical installations are carried out with faults.
- approx. DKK 30bn in the form of reduced productivity and absence due to illness because of a poor indoor climate (Wargocki et al, 2000) (Fisk and Resenfeld, 1997) (Wyon, 1996).

There are many reasons why HVAC installations are not functioning optimally: some are wrongly dimensioned, some have installation defects, some are commissioned wrongly, the conditions have changed, e.g. as a result of altered use of the building, some are poorly maintained, many have too limited control possibilities, …. and often, the possibility for the operational staff is poor or their knowledge is not good enough to carry through an optimal plant control.

Typically, the operation of buildings and installations takes place today with traditional building automation, which is characterised by

- being based on static considerations
- the individual sensor being coupled with one actuator/valve, i.e. the sensor's signal is only used in one place in the system
- subsystems often being controlled independently of each other
- the dynamics in building constructions and systems which is very important to the system and comfort regulation is not being considered.

This, coupled with the widespread tendency to use large glass areas in the facades without sufficient solar shading, means that it is difficult to optimise comfort and energy consumption. Over the last 10-20 years there has, therefore, been a steady increase in the complaints regarding the indoor climate in Danish buildings and, at the same time, new buildings often turn out to be considerably higher energy consuming than expected.

Other trends in the building industry are

- increased demands regarding comfort
- installation costs constitute a steadily increasing part of the total costs
- increasing demands for interaction between buildings and installations
- increased use of IT
- steadily increasing number of sensors in components

The increased use and capacity of microprocessors, as well as many components in building and installations being born with sensors, increase the possibility of better interplay between the building and the installations, as still more powerful tools appear within areas as data collection, data processing, statistics, mathematical modelling, etc. This gives rise to huge possibilities which, however, are far from exploited today.

1.1. Multi parameter controllers

One way of dealing with the above problems in buildings is to utilize multi parameter controllers. Multi parameter controllers are - as shown in figure 1 - a combination of physical and virtual sensors. The physical sensor signals may be temperature, air speed, pressure, CO_2, relative humidity, solar radiation but also information on the position of valves, the speed of fans, the power supply to motors, the heating demand etc. Based on the signals from the physical sensors it is possible to generate virtual sensor signals, which cannot or are very difficult to measure but which more precisely characterise the actual condition of the building and installations. This will make a more optimized operation of the building and installations possible leading to reduced energy demand and improved indoor climate.

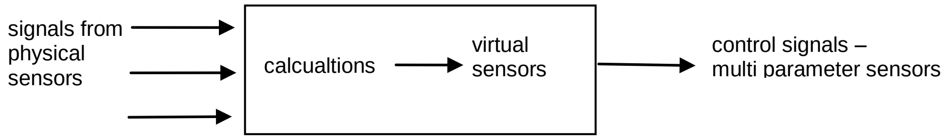


Figure 1. The principle of multi parameter sensors.

One example of a multi parameter sensor is the comfort equation by Fanger (Fanger, 1970). Using input from physical sensors: temperature, radiation asymmetry, air speed and relative humidity together with information of the level of activity and clothing it is possible to determine the percentages of people who would be dissatisfied with the actual indoor climate. The result is a virtual sensor signal which cannot be measured directly and continuously. It can only be found by asking people by eg questioners – which of course cannot give continuous values. Fangers equation, however, may be applied for continuously monitoring of the indoor climate without disturbing the persons in a room with questions. If this virtual sensor signal is used to control the installations Fangers equation is enhanced from a multi parameter sensor to a multi parameter controller.

The comfort equation by Fanger is based on many years of research. The number of input parameters in the Fanger type of empirical/mathematical/parametric equation is however too limited in order to evaluate the performance of an entire building.

The term multi parameter controllers may be enhanced by switching from the above parametric type of correlation to non parametric correlations based on statistical analysis and treatment of the signals from the physical sensors. Using this technique the number of input signals from the physical sensors may in principle be infinite. The technique further allows that insignificant signals are excluded so that their influence, although small, doesn't lead to a wrong characterization of the conditions in the building and installations. There is no need for deterministic correlations between the many sensor signals. The correlations are obtained by means of advanced statistical and mathematical data analysis and mathematical modelling. The multi parameters may be tailored to fit the actual purpose.

When controlling buildings and installations there are many non or difficult measurable conditions of main importance for the control of the building and installations – eg the indoor climate. The main purpose of buildings is to ensure a good indoor climate – however, the indoor climate is complex as it consists of thermal indoor climate, air quality, light conditions, acoustic, working environment, etc. - all areas where it is difficult to measure the actual conditions using traditional measuring instruments. The multi parameter sensor has its strength here as it by means of traditional sensor signals is able to generate virtual sensor signals which better characterise the actual conditions - of which Fangers comfort equation may be a part of.

It is, therefore, anticipated that the development of multi parameter sensors and multi parameter controllers will be a major step forward in the direction of more optimal controlled buildings and installations with a minimized energy demand and increased indoor comfort.

A better characterization of buildings and installations will most often by itself lead to a better understanding of the actual conditions which again may lead more optimized control of the buildings and installations. However, for an optimal control it is necessary to use online characterisation for an online control of the building and installations – ie that the multi parameter sensors are transformed to multi parameter controllers.

1.2. Purpose of the project

The purpose of the present project is to investigate the type of multi parameter sensors which may be generated for buildings and further to carry out a preliminary evaluation on how such multi parameter controllers may be utilized for optimal control of buildings.

The aim of the project isn’t to develop multi parameter controllers – this would require much more effort than possible in the present project. The aim is to show the potential of using multi parameter sensors when controlling buildings and to get a first understanding on how to use sensor data for diagnostics.

For this purpose a larger office building was chosen – an office building with high energy demand and complaints regarding the indoor climate – see chapter 2. In order to obtain data for the project a data logging facility was installed in the Building Management System (BMS) of the building – see chapter 3.

The aim of the project is to log whatever is available from a traditional BMS (only few extra sensors were added) in the form of sensor signals, set points, valve positions, energy demand, etc. and by means of advanced statistics and mathematical modelling to investigate the possibility of generating multi parameter sensors. The aim is thus to investigate how control via traditional BMS can be enhanced by adding multi parameter sensors and controllers.

Another aim is to investigate how the availability of the above mentioned time series may enhance traditional inspections of the building and installations.

Due to more work on the logged data than foreseen focus has been put on handling of data and visual inspection of time series rather than on multiparameter sensors.

2. The building and installations

The building Tuborg Boulevard 12 – chosen for the project - is situated in a newer build-up area mainly containing larger office buildings situated in the northern outskirt of Copenhagen. Figure 2.1 shows an aerial view of the building.

Figure 2.1. Tuborg Boulevard 12.

The building is as seen in figure 2.1 a non rectangular shaped building with an atrium in its central part. The foot print of the building is 4,946 m². It is a five storey building with a basement. The total floor area from the Danish Building Register is 21,199 m² of which 18.726 m² are heated. The floor area of the atrium is 1,182 m².

Figures 2.2-2.9 show pictures of the building.

Figure 2.2. The West façade. Orientation: 31° from West towards South.

Figure 2.3. The South façade. Orientation: 15° from South towards East.

Figure 2.4. The East façade. Orientation: 15° from East towards North.

Figure 2.5. The North West façade. Orientation: 35° from North towards West

Figure 2.6. The atrium seen towards South.

Figure 2.7. The atrium seen towards North West.

Figure 2.8. The roof of the Atrium.

Figure 2.9. The roof of the atrium seen from outside.

2.1. Constructions

Figures 2.2-2.9 show that the main part of the thermal envelope consists of glazing. There are four main types of glazing in the building:

- transparent glazing in the facade
- opaque glazing in the façade – this is shown in figure 2.10
- transparent glazing in the roof
- transparent glazing facing the atrium

Figure 2.10. Opaque glazing in the façade.

2.2.1. Glazing

external: 6 or 8 mm Stopray Elite 67/37
14 or 16 mm with Argon
internal: 4 or 6 mm clear float
U-value: 1.12 W/m²K
g-value: 0.4

Opaque glazing in the façade located in front of the supporting columns:

external: 6 mm hardened float
14 mm air
internal: 6 mm hardened glass with enamel on side 4
U-value: 2.8 W/m²K

Transparent glazing in the roof - skylight:

external: 6 mm Silver 43/25
15 mm with Argon
internal: 6 mm safety glass
U-value: 1.12 W/m²K
g-value: 0.27

3% of the skylight can be opened for smoke ventilation and conditioning of the atrium.

Transparent glazing facing the atrium:

external: 6 mm clear float
14 mm air
internal: 4/1/4 mm laminated clear float
U-value: 2.8 W/m²K

U-values incl. framing

There is no information of these U values. They are instead estimated to be:

Transparent glazing in the façade:	1.3-1.5 W/m²K
Opaque glazing in the façade:	2.8 W/m²K
Transparent glazing in the roof:	1.3-1.5 W/m²K
Transparent glazing facing the atrium:	2.8 W/m²K

Solar shading

Façade:

There are no external shading devices on the building. However, internal venetian blinds and computer curtains are available in most rooms facing the façade. Half of the Southwest facing façade (the red arrow in figure 2.1) has a double façade with venetian blinds between the two sets of glazing – energy glazing outside and single glazing inside. All blinds and curtains are manually controlled.

Curtains under the roof lights:

There are horizontal solar curtains installed under the roof light in the atrium – see figure 2.12 in order to decrease overheating risk and light level in the atrium due to incoming solar radiation. These open and close automatically.

2.1.2. Opaque constructions

External walls:

external: 30 mm natural stones
20 ventilated air gap
150 mm mineral wool (Venti-bats)
internal 200 mm concrete
estimated U-value: 0.23 W/m²K

Floor above basement:

Atrium:

from top:20 mm granite
60 mm mortar
105 mm concrete with heating tubes
50 m hard insulation
hollow core floor slap
100 mm insulation
25 mm lathing
25 mm wood-wool
estimated U-value: 0.23 W/m²K

Kitchen:

from top: tile
hollow core floor slap
100 mm mineral wool
25 mm lathing
25 mm wood-wool
estimated U-value: 0.32 W/m²K

Canteen:

from top: parquet flooring on laths
hollow core floor slap
100 mm mineral wool
25 mm lathing
25 mm wood-wool
estimated U-value: 0.32 W/m²K

Roof

external: roofing felt
TF insulation
wedge-shaped insulation – slope 1:40
hollow core floor slap
estimated U-value: 0.1 W/m²K

Vertical part of the roof light:

external: steel plate
125 mm insulation
steel plate
16 fibre board
20 mm air gap
perforated steel plate
estimated U-value: 0.28 W/m²K

2.2. Installations

2.2.1. Heating system

The building is heated by district heating.

Space heating in the working areas is supplied by means of radiators along the façade of the building – see figure 2.11, while the atrium is heated via floor heating and convectors just under the skylight - the latter in order to prevent downdraft – see figure 2.12. There are further heat recovery and heating coils in the ventilation systems for heating the fresh air to the building during periods with low ambient air temperature.

Figure 2.11. Example of a radiator along the façade.

2.2.2. Ventilation systems

There are 11 ventilation systems in the building.

- Vent1, Vent2, Vent3, Vent4 and Vent7 are balanced ventilation systems with heat recovery
- UDS1, UDS2, UDS3, UDS4 and Vent6 are exhaust ventilation systems
- Vent5 is a fan for moving air in the parking space in the basement towards the exhaust fan of the parking space

Figure 2.12. Convectors and curtains under the skylight in the atrium.

Ventilation systems Vent1, Vent2 and Vent3 serve each approximately one vertical third of the working areas in the building as indicated in figure 2.13.

The ventilation systems are all located in the basement. Table 2.1 shows the designed air flow volumes of the ventilation systems.

Ven1-3 and Vent7 have all heat recovery with a rotating wheel with an efficiency of: Vent1 and 3: 74.5 %, Vent2: 74 % and Vent7: 76.4% at the dimensioning flow rates stated in table 2.1. The heat recovery in Vent4 is fluid clutched batteries with an efficiency of 45.3 %.

In Vent1-4 and Vent7 there are cooling coils for conditioning of the fresh air in order to prevent the building from overheating.

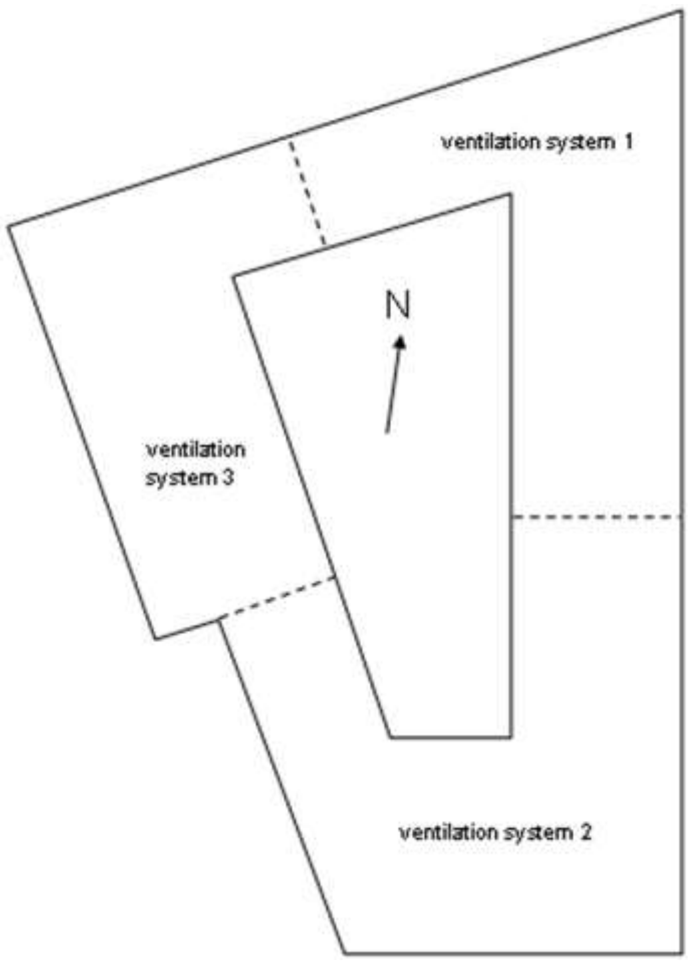


Figure 2.13. The vertical division of the building for Vent1-3.

Ventilation System	Fresh air m³/h	Exhaust air m³/h	Main function
Vent1	25,600	25,600	Conditioning of office spaces
Vent2	27,600	27,600	Conditioning of office spaces
Vent3	25,600	25,600	Conditioning of office spaces
Vent4	19,370	13,440	Conditioning and exhaust of kitchen and canteen
Vent5	-	2 x 20,000	Air circulation in parking space in the basement
Vent6	-	4,000/8,000	Exhaust from the room with the refrigeration plants
Vent7	3.492	3.492	Conditioning of education room on the first floor located at the South end of the building – see figure 2.14
UDS1	-	2,270	Exhaust from toilets
UDS2	-	2,270	Exhaust from toilets
UDS3	-	2,270	Exhaust from toilets
UDS4	-	6,575	Exhaust hoods in the kitchen

Table 2.1. Designed air volume flows of the ventilation systems in the building.

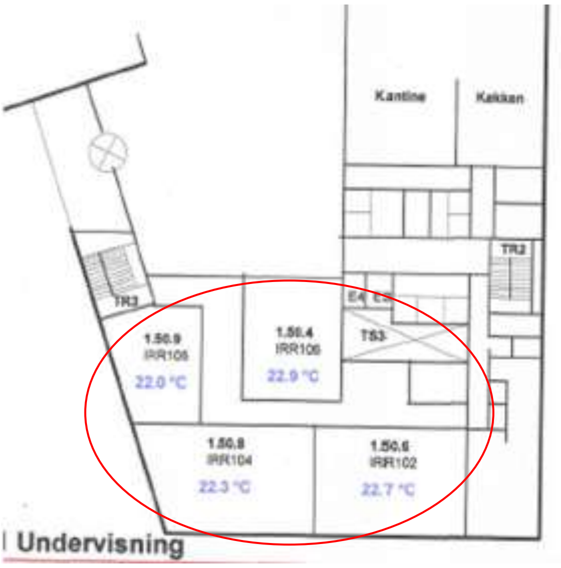


Figure 2.14. Seminar rooms on the first floor conditioned by Vent7.

2.2.3. Cooling systems

The solar gain and internal load of the building are very high. It is therefore necessary to cool the building by means of two cooling systems located in the basement of the building.

The larger system (system 1) with a nominal capacity of 730 kW cools water to the cooling coils of the ventilation systems. The designed temperature set is 6/12°C.

The smaller system (system 2) with a nominal capacity of 225 kW cools water to active cooling baffles located in the ceiling in the workspaces (see figure 2.15). The designed temperature set is 15/18°C.

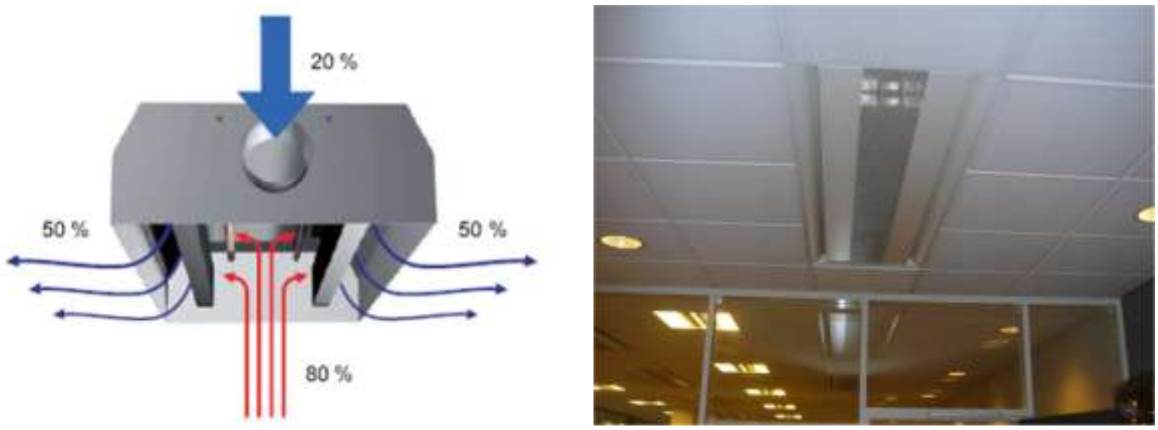


Figure 2.15. The principle of active cooling baffles to the left and an example of cooling baffles in the ceiling at Tuborg Boulevard 12.

The cooling systems are via a secondary cooling circuit connected to four dry coolers at the South end of the roof of the building – see figure 2.1. When the ambient temperature drops below a certain limit it is possible to cool the building via free cooling. The water to the cooling baffles can be cooled directly by the dry coolers without starting the compressor of cooling system 2 – this saves energy.

User installations

The tenants of the building have installed their own cooling systems for cooling server rooms. The compressor and condenser of these systems are located in the parking space in the basement as shown in figure 2.16. The electricity to these cooling systems is paid directly by the tenants via their electricity bill.

Figure 2.16. User installation in the basement for cooling of server rooms.

2.3. Use of the building

The building was put into operation on May 5th, 2002.

There are three tenants in the building:

Dan-Ejendomme – property management company
Microsoft – sale of computer hardware and software
Regus – runs office hotels

They occupy the following floors:

Ground floor:	Kitchen, canteen, Dan-Ejendomme and seminar rooms for Microsoft
1st floor:	Dan-Ejendomme
2nd floor:	Microsoft
3rd floor:	Regus
4th floor:	Microsoft

It has not been possible to obtain information on the number of people working in the building.

Two different ways of organizing the floors have been applied:

Dan-Ejendomme and Microsoft:	mainly open-plan offices and few smaller offices and meeting rooms – see figure 2.17
Regus:	only smaller offices – figure 2.18

2.3.1. Thermal loads and temperatures

The following thermal loads were used when designing the building and installations:

- Persons	100 W/person
- PCs: there was assumed 1.2 pc/person (1 pc: 100 W)	120 W/person
- Artificial light	
In offices	15 W/m²
Areas with special lightning (canteen, foyers, etc)	30 W/m²
- Person load in offices	10 m²/person
- Person load in meeting rooms and canteen	2 m²/person

The above thermal loads occur between 9 am and 18 pm.

The flow rate of fresh air should be at least 10 l/s/person.

The indoor air temperature should stay between 20 and 24°C during the winter and between 23 and 26°C during the summer. The indoor air temperature in the offices must not exceed 26°C in the period June-August during more than 110 hours and 27°C during more than 30 hours. In the meeting rooms the indoor air temperature may not exceed the two above temperatures in more than 100 and 25 hours. The temperature of rooms with installations should stay between 19 and 30°C and in copy/printer rooms between 20 and 26°C.

2.4. Energy label and comfort

Figure 2.19 shows the Energy label for Tuborg Boulevard 12. The measured energy and water demand are for the period January 1, 2003 – December 31, 2003

A “C” for heating is reasonable given that a considerable percentage of the external walls are glazed. However, the “C” does not describe the building very well as it is the outcome of high internal and solar gains, which of course reduce the heating demand of the building. This is seen when looking at the poor “E” for the electricity demand. Much electricity is needed in order to cool the building – not only during the summer, but all year round.

This will be dealt with in chapter 5.

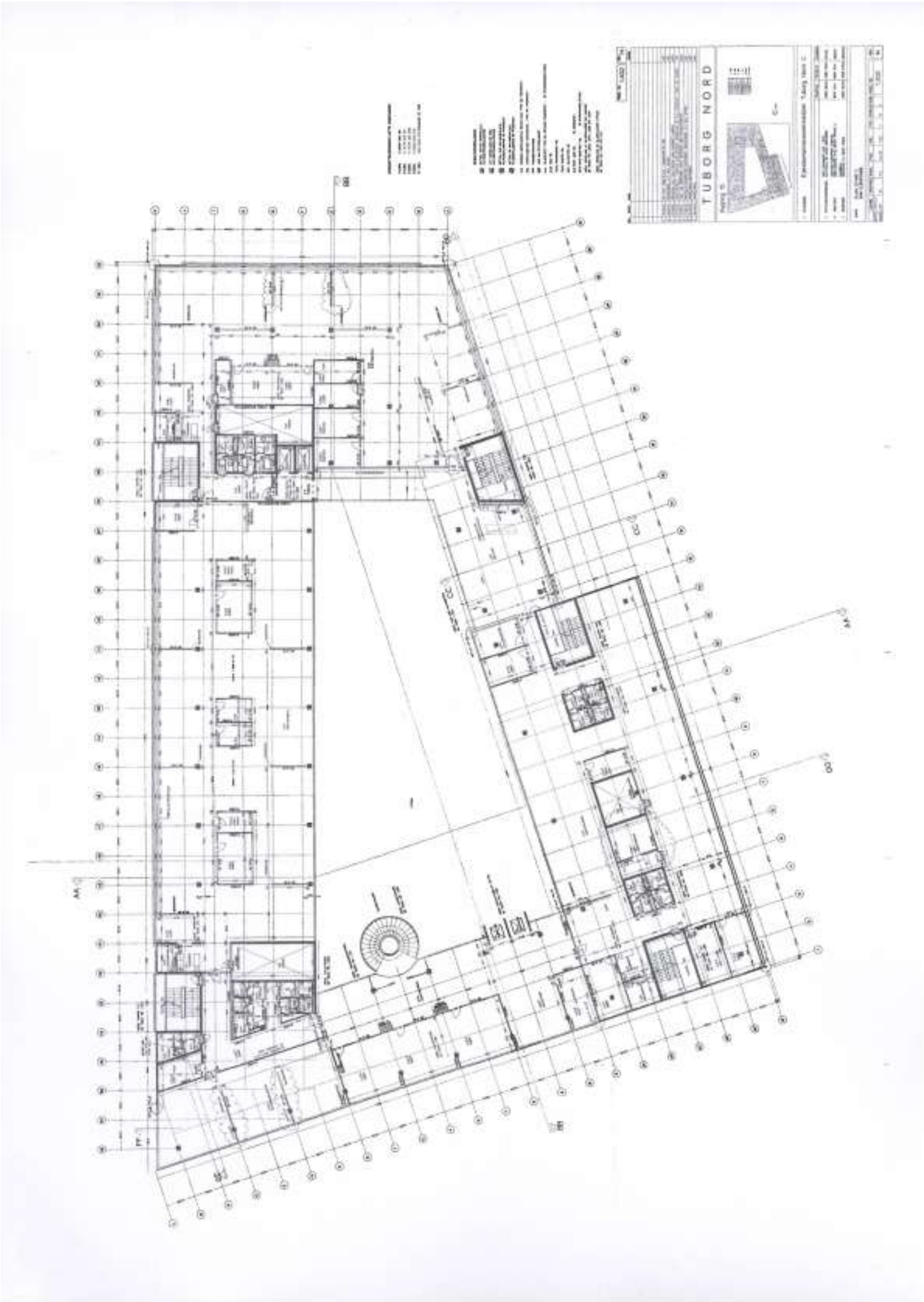
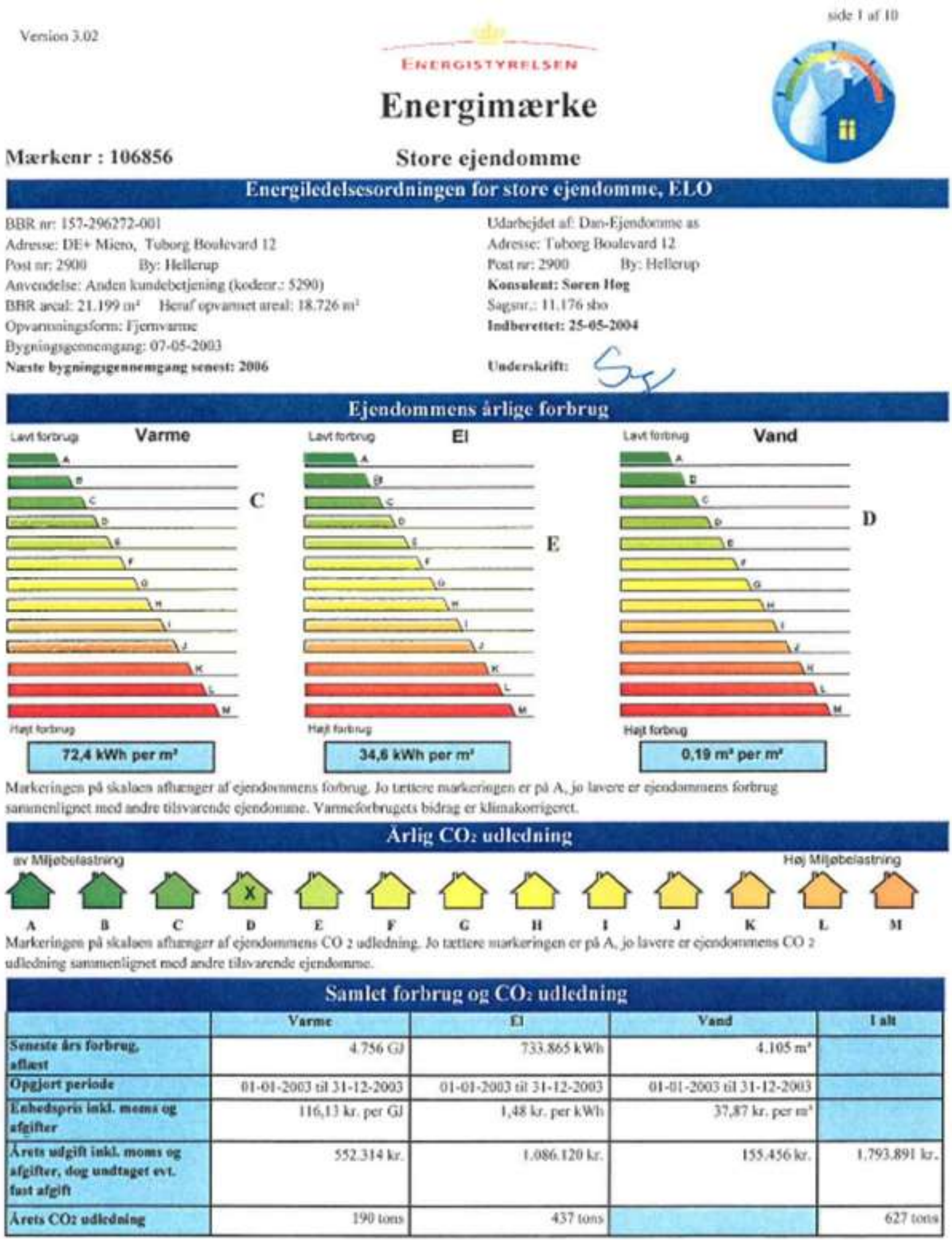


Figure 2.17. Example of floor plan with open-plan offices and few smaller offices and meeting rooms.

Figure 2.18. Example of floor plan with smaller offices.



Version 3.02

side 1 af 10

ENERGISTYRELSEN

Energimærke

Mærkenr : 106856

Store ejendomme

Energiledelsesordningen for store ejendomme, ELO

BBR nr: 157-296272-001
Adresse: DE+ Micro, Tuborg Boulevard 12
Post nr: 2900 By: Hellerup
Anvendelse: Anden kundebetjening (kodenr.: 5290)
BBR areal: 21.199 m² Heraf opvarmet areal: 18.726 m²
Opvarmningsform: Fjernvarme
Bygningsgennemgang: 07-05-2003
Næste bygningsgennemgang senest: 2006

Udarbejdet af: Dan-Ejendomme as
Adresse: Tuborg Boulevard 12
Post nr: 2900 By: Hellerup
Konsulent: Søren Høg
Sagsnr.: 11.176 sho
Indberettet: 25-05-2004

Underskrift:

Ejendommens årlige forbrug

Markeringen på skalaen afhænger af ejendommens forbrug. Jo tættere markeringen er på A, jo lavere er ejendommens forbrug sammenlignet med andre tilsvarende ejendomme. Varmeforbrugets bidrag er klimakorrigeret.

Årlig CO_2 udledning

Markeringen på skalaen afhænger af ejendommens CO_2 udledning. Jo tættere markeringen er på A, jo lavere er ejendommens CO_2 udledning sammenlignet med andre tilsvarende ejendomme.

Samlet forbrug og CO_2 udledning

	Varme	El	Vand	I alt
Seneste års forbrug, aflæst	4.756 GJ	733.865 kWh	4.105 m³	
Opgjort periode	01-01-2003 til 31-12-2003	01-01-2003 til 31-12-2003	01-01-2003 til 31-12-2003	
Enhedspris inkl. moms og afgifter	116,13 kr. per GJ	1,48 kr. per kWh	37,87 kr. per m³	
Årets udgift inkl. moms og afgifter, dog undtaget evt. fast afgift	552.314 kr.	1.086.120 kr.	155.456 kr.	1.793.891 kr.
Årets CO_2 udledning	190 tons	437 tons		627 tons

Figure 2.19. The energy label for the building from 2004 (in Danish).

3. Data collection

The purpose of the project was to investigate how logged values from a traditional Building Management System (BMS) may be utilized for generation of multi parameter sensors and controllers. For that reason a logging system was implemented in the BMS system of the building described in chapter 2. Few extra sensors were included in the BMS system and data were further obtained from DONG Energy and from locally placed autonomic data loggers.

In total 1050 data point (parameters) were logged. The data points from the BMS system were mainly logged every five minutes while a few were logged every ten minutes. The autonomic data loggers logged every 15 minute, while the data from DONG Energy were hourly values.

The logging started on July 1, 2007 and ended on August 31, 2008. All data are unfortunately not present for the whole period – see later.

The logged values will be described in chapter 3.1 while the database containing the measured values will be described in chapter 3.2.

3.1. Logged data

The description of the logged data will be divided in three sections: data from the BMS system, data from DONG and data from the autonomic data loggers.

3.1.1. BMS system

975 data points in the BMS system were logged. The data from the BMS systems is divided into the following categories:

- weather station
- heating systems
- ventilation systems
- cooling systems
- offices
- roof light

Weather station

Figure 3.1 shows a screen dump of the BMS screen of the weather station. The weather station is located on top of another building in the area.

The following values were logged from the weather station:

- total solar radiation on horizontal
- ambient temperature
- lux (lumination)
- wind speed
- wind direction

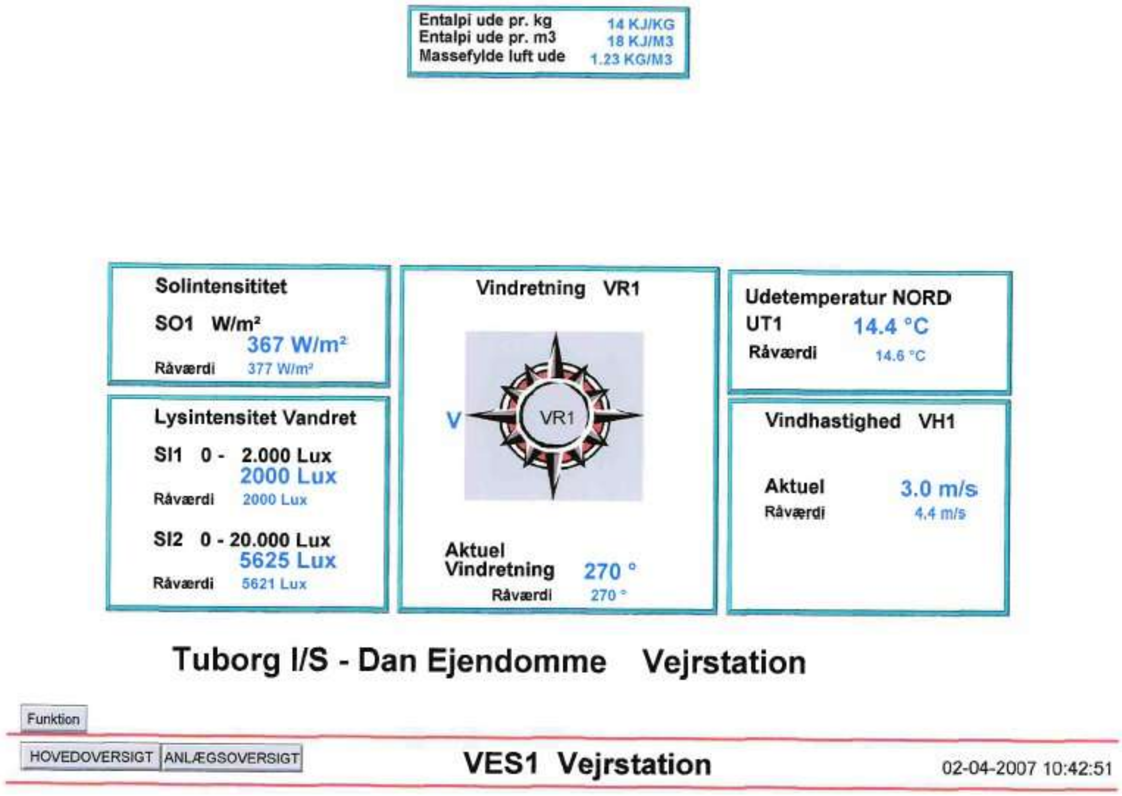


Figure 3.1. Screen dump of the BMS screen concerning the weather station (in Danish).

Heating systems

The measurements for the heating systems are divided into four subsystems:

- district heating
- radiator system in the offices
- floor heating in the atrium
- ribbed heating tubes under the glazed ceiling of the atrium

District heating

- energy consumption of district heating

Radiator system in the offices

The following parameters were logged:

- min. room temperature in the offices – found by the BMS system
- position of the valve regulating the flow
- set point: max room temperature
- set point: min room temperature
- set point: min room temperature during the night
- calculated supply temperature to the radiators
- measured supply temperature to the radiators
- set point: ambient temperature at which the radiator system stops

Figure 3.2 shows a screen dump of the BMS screen of the radiator systems.

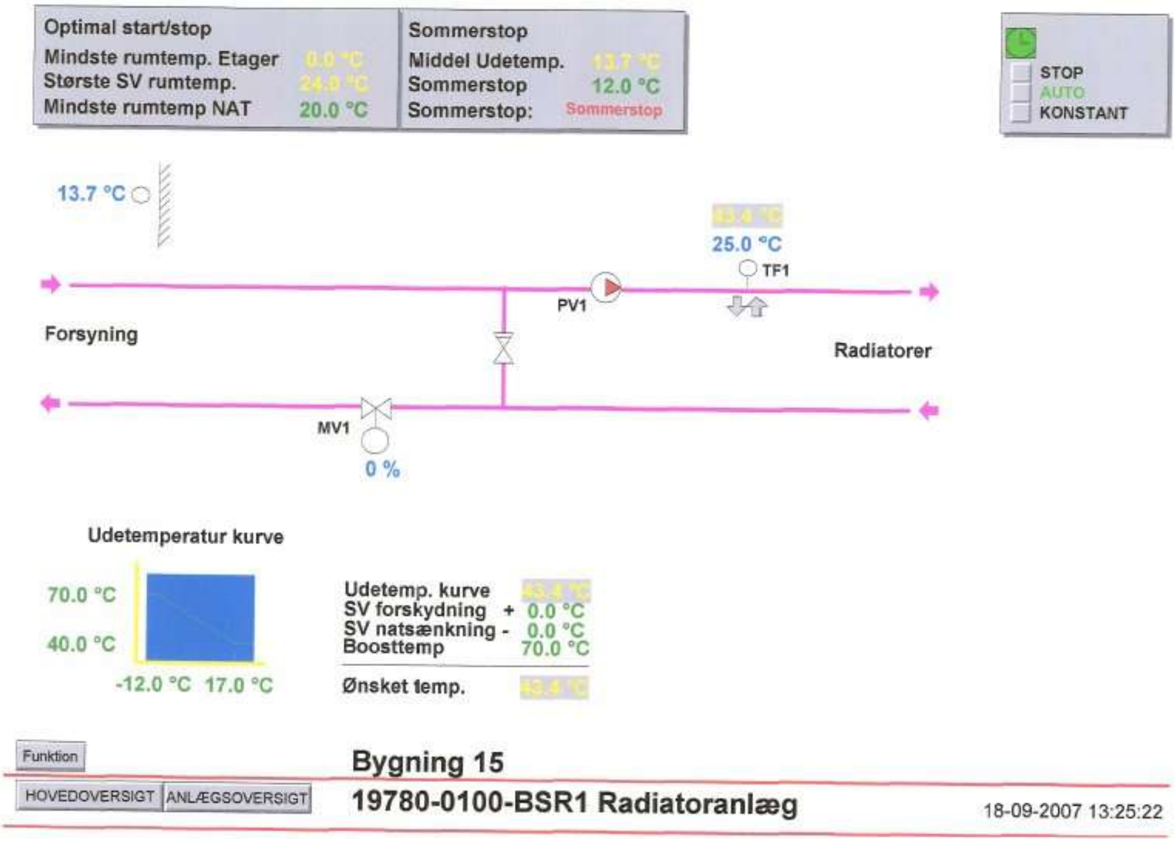


Figure 3.2. Screen dump of the BMS screen concerning the radiator system (in Danish).

Floor heating in the atrium

The following parameters were logged:

- position of the valve regulating the flow
- measured room temperature
- set point: room temperature
- calculated supply temperature to the floor heating
- measured supply temperature to the floor heating

Ribbed heating tubes under the glazed ceiling of the atrium

The following parameters were logged:

- position of the valve regulating the flow
- calculated supply temperature to the ribbed tubes
- measured supply temperature to the ribbed tubes
- set point: ambient temperature at which the heating starts

Ventilation systems

Several parameters were logged on ventilation systems 1, 2, 3 and 7. The logging was identical for ventilation system 1, 2 and 3 as these are identical while different for ventilation system 7 as the latter was installed later. Ventilation system 7 only serves a few seminar rooms at the ground floor.

Ventilation system 1, 2 and 3

The following parameters were logged:

- CO_2 in the exhaust air – new sensor as part of the project
- dew point of the exhaust air – new sensor as part of the project
- relative humidity of the exhaust air – new sensor as part of the project
- position of the valve for cold water from cooling system 1 to CAV part
- position of the valve for cold water from cooling system 1 to VAV part
- position of the valve for warm water from district heating
- measured pressure in the VAV system
- set point: pressure in the VAV system
- measured pressure in the exhaust
- set point: pressure in the exhaust
- max air temperature in the rooms served by the ventilation system*
- min air temperature in the rooms served by the ventilation system*
- measured supply air temperature to CAV
- set point: supply air temperature to CAV
- measured supply air temperature to VAV
- set point: supply air temperature to VAV
- return air temperature from the building
- speed of the rotating heat exchanger
- speed of the fresh air fan
- speed of the exhaust fan

*max and min room temperature are fictive temperature series logged by the BMS. The BMS takes for each time step the room temperature from the room with the highest room temperature and the lowest room temperature.

Figure 3.3 shows a screen dump of the BMS screen of ventilation system 1

Ventilation system 7

The following parameters were logged:

- CO_2 in the exhaust air – new sensor as part of the project
- relative humidity of the exhaust air – new sensor as part of the project
- position of the valve for cold water from cooling system 1
- position of the valve for warm water from the district heating
- speed of the rotating heat exchanger
- measured supply air temperature to the rooms
- set point: supply air temperature to the rooms
- return air temperature

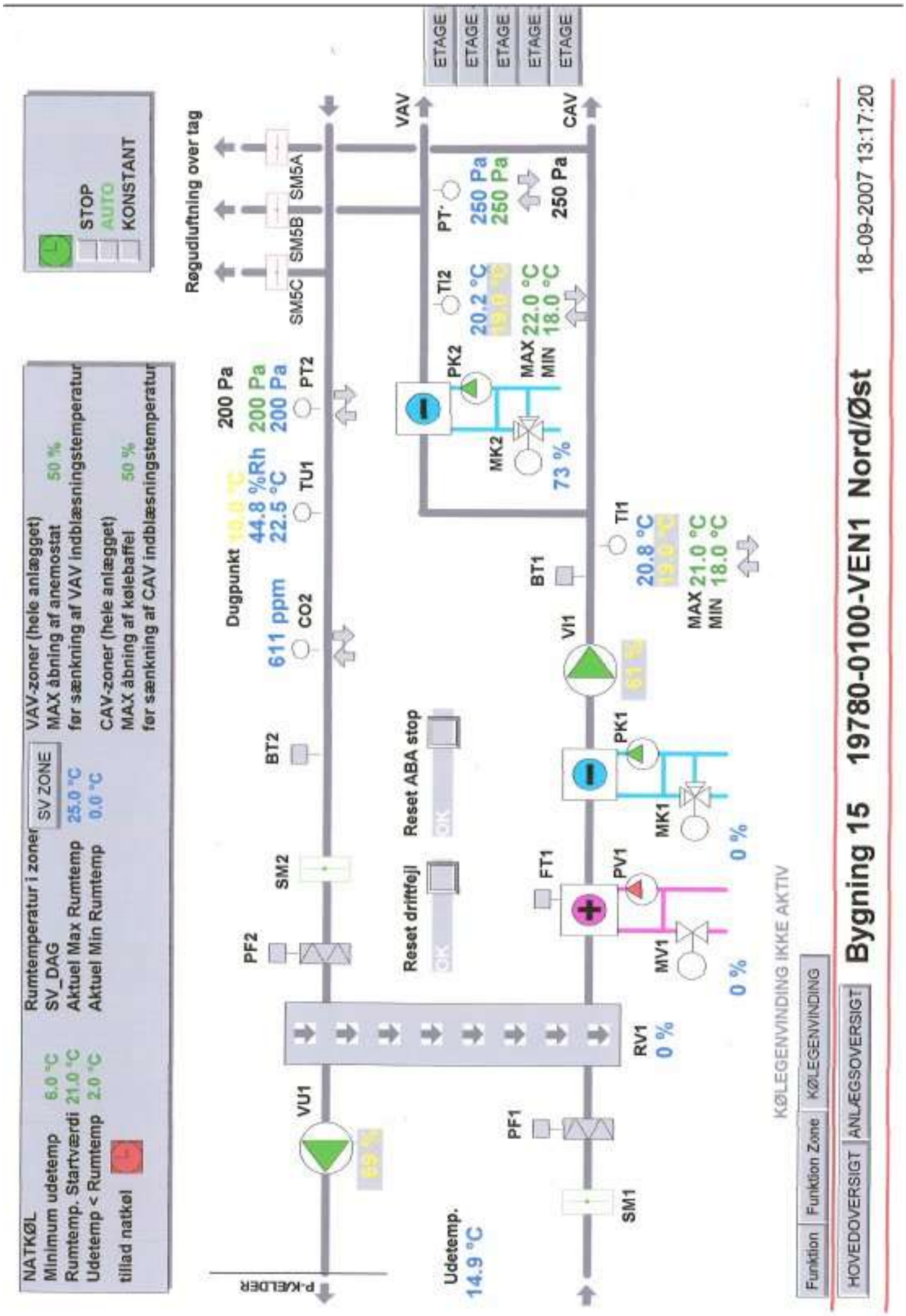


Figure 3.3. Screen dump of the BMS screen concerning ventilation system 1 (in Danish).

Cooling systems

The following parameters were logged:

- electricity demand of cooling system 1
- measured supply temperature for cooling system 1
- measured return temperature for cooling system 1
- electricity demand of cooling system 2
- measured supply temperature for cooling system 2
- measured return temperature for cooling system 2

Offices

The office spaces in the building are divided into zones. The zones are either a room or part of an open-plan office as seen in figure 3.5.7

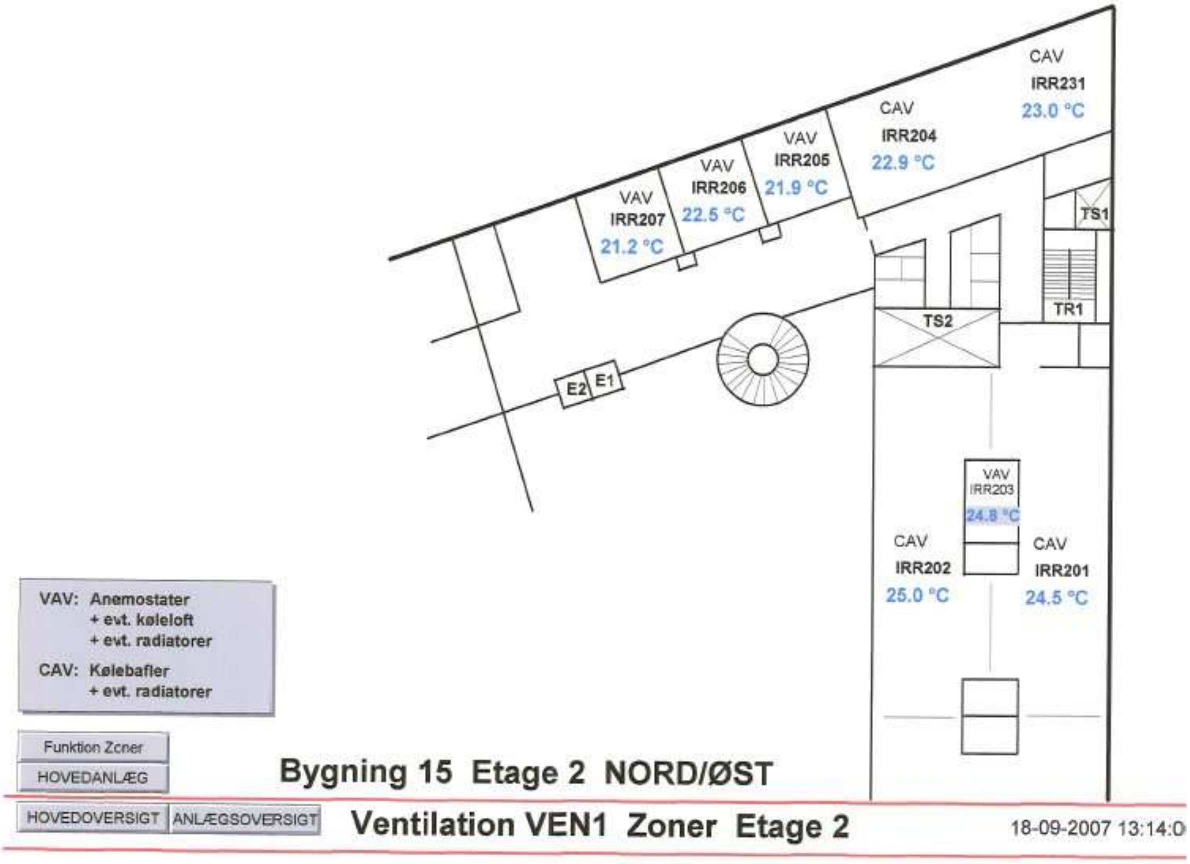


Figure 3.5. Screen dump of the BMS screen concerning zones in the office spaces (in Danish).

The following parameters have been logged for zones supplied by ventilation system 1, 2 and 3:

- the position of the valve for the cooling baffles
- the position of the valve for the radiators
- the measured room air temperature
- set point: room air temperature

Figure 3.6 shows a screen dump of the BMS screen of an arbitrary zone.

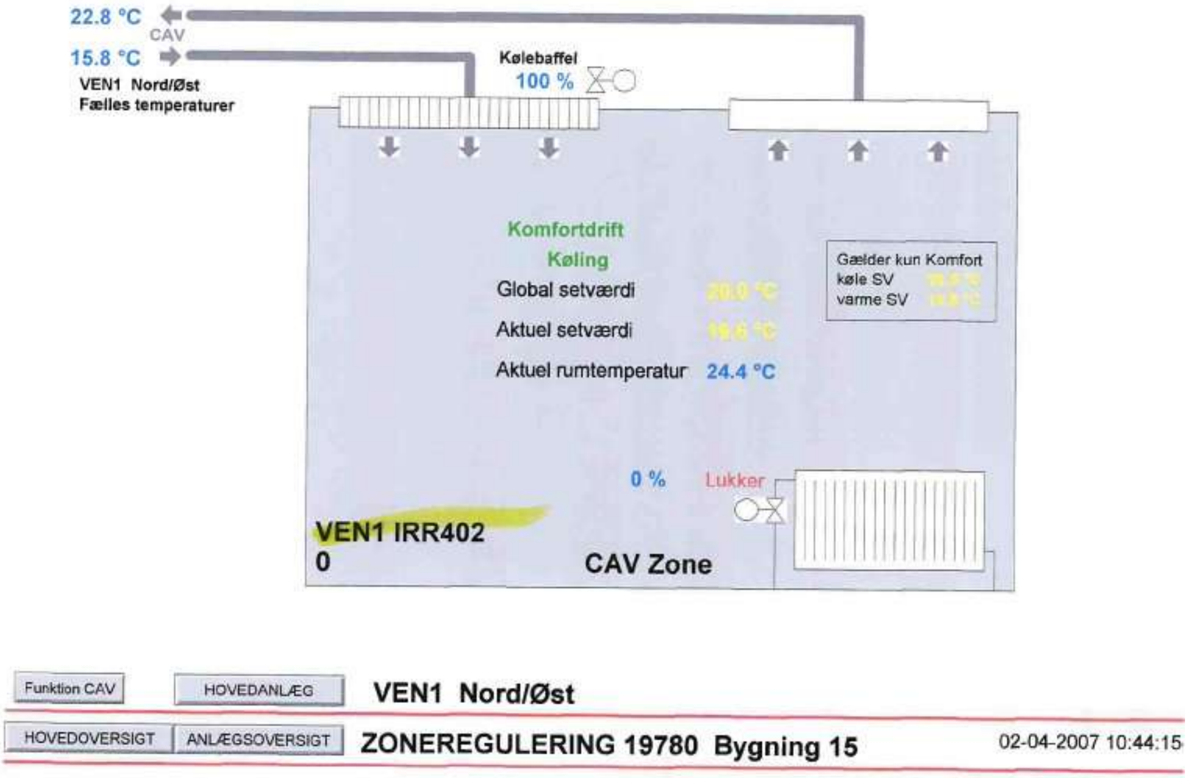


Figure 3.6. Screen dump of the BMS screen concerning zones (in Danish).

The following parameters were logged for zones supplied by ventilation system 7.

- if the cooling baffles are active or not
- the measured room air temperature
- set point: room air temperature
- the position of the valve for the radiators

Roof light

The following parameters were logged for the windows in the roof of the atrium.

- air temperature in the top of the atrium
- set point: air temperature in the atrium at which the windows open and close
- if the windows are open or closed

The following parameters were logged for the solar curtains.

- if the solar curtains are open or closed

Electricity to the installations

- electricity demand of the technical installations

3.1.2. Data from DONG Energy

Accumulated readings from seven electricity meters were received as hourly values from DONG Energy. The seven electricity meters measured the following demands:

- common installations – ventilation, cooling, etc.
- building management office
- Dan-Ejendomme
- Microsoft ground floor and fourth floor
- Microsoft second floor
- Regus
- kitchen

3.1.3. Autonomic data loggers

In the scope of indoor climate evaluation, autonomic data loggers were located in 17 different office spaces. The measuring equipment and location of these are described in chapter 4. The measurements are 15 minutely values and are not continuous. The measurements comprise:

- air temperature
- relative humidity
- light level (Lux)
- CO_2 level

3.2. Database

The data is received in files from the different data providers. It is necessary to integrate the data and to make it available to different kinds of applications, e.g. statistical tools or MS Excel.

The best way to do this is to store the data into a database. A database is a tool to organize data in files in the file system in a way, which makes reading and manipulation effective. There are many commercial database systems on the market. There are also free, open source products, notably MySQL. MySQL is available for all common platforms and is highly scalable. That means it will be able to hold very large amounts of data, which is necessary in the present project. Furthermore there is a suite of GUI-tools, i.e. graphical interfaces to the database, which are conveniently used in place of the quite cumbersome standard text-based interfaces.

3.2.1 Products

The following products were used:

- MySQL Community Server
    - MySQL 5.0.51
- GUI Tools
    - MySQL Administrator 1.2.12
    - MySQL Query Browser 1.2.12
- Connectors

- ODBC 3.51

The ODBC connector is used for connecting applications to the database, for instance MS Excel. There is a newer version than 3.51, but the old one proved more robust across platforms.

All products are downloaded from www.mysql.com.

The platforms in use were

- Windows XP and Vista
- Mac OS X Leopard 10.5
- Linux

For transforming text files between different kinds of encodings another free product was used:

- Smultron

which is very effective for that purpose.

For reporting purposes we have used

- MySQL Query Browser
- Microsoft Excel
- R

MS Excel proved inadequate for the large database. R has been the main tool and is described Appendix 6 and 7.

3.2.2 Handling data

The concepts used for handling data in this project are from the disciplines of Business Intelligence (BI) and datawarehousing. BI is a general term used for a reporting platform where data is collected from source systems and provided to reporting tools.

The arrows in figure 3.7 represent data flows during which transformations may take place. In BI jargon this is called ETL-processes, i.e. Extract, Transform and Load.

This concept is widely used throughout the industry and business, and many dedicated tools have been developed for data handling as well as for reporting. A number of BI-suites exist for this purpose. In the present project we don't use such tools, but stay with simple SQL scripts and easily accessible reporting tools.

The reason for the success of the concepts of BI and datawarehousing is because data is gathered from different sources and are brought together in a common database using a common data structure from where it can be accessed.

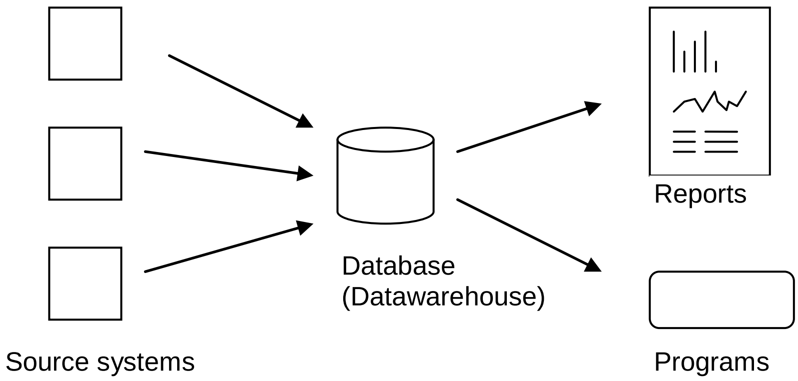


Figure 3.7. Data flow in report environment.

In this project the BI scheme was implemented in the following way:

Source systems
Data was received from the source systems as text files or Excel files. When receiving files with source data from the data providers, the data was transformed into conformed formats: Text files were transformed to correct encoding (interpretation of letters in a text file), whereas data in Excel-files was extracted, encoded and stored as text files.

Database
Data was then loaded to the database, cf. below. Unlike other database systems, MySQL allows the user to select among different file formats for storing the database. The term Storage Engine is used for applications storing and accessing data in these files. In this project the classic MyISAM was user for different reasons:

1) It is highly effective for reporting purposes (in contrast to e.g. transaction handling), i.e. it is convenient for extracting data from the database.
2) Files exist in the file system for each table in the database together with files containing indexes for the tables. This very simple file structure makes exchange of data less complicated. The folder containing data and indexes can simply be copied and distributed.

When data is stored in a database such as MySQL it becomes rigid in the sense that unlike text files it can be exchanged between different operators and platforms without loosing validity and conformity.

Distribution of data
In a BI setup data are distributed to end users through dedicated channels. Typically some reporting tool is used, which has access to the database and where user access is controlled. In our pilot project setup the situation was completely different. Here different project participants had completely different working environments, i.e. different operative systems, separate networks etc.

The distribution method adopted eventually was to copy the folder with the data files to a portable hard drive and then copy the folder with content to the local hard drive. Finally the path-variable of the database is changed to point at the new folder – this is most conveniently done with the MySQL Administrator. When working with R DTI eventually got remote access to the DTU network and database.

In the final version the files, including indexes, took up some 15 GB of storage.

3.2.3 The dimensional data model

In a database data is stored in tables. The data model of the database is the structure of the tables. As an illustration one can consider temperature measurements from a sensor in room 312 on the third floor. In a normalized data model each piece of information must exist only once in the database. Thus there would be a table with the floors, a table with the rooms, and a table with the temperatures:

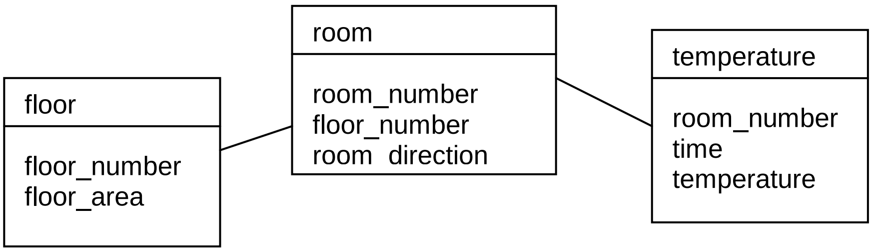


Figure 3.8. Normalized data model: no redundancy.

In this example the floor table has two columns, floor_number and area. In the floor table there will be a row representing the third floor. In the room table there will be a row representing room 312, and in the temperature table, there will be a large number of rows representing measurements.

A normalized data model results in a large number of tables. For reporting purposes with massive amounts of data this is very inefficient. The star schema is another kind of data model with some redundancy:

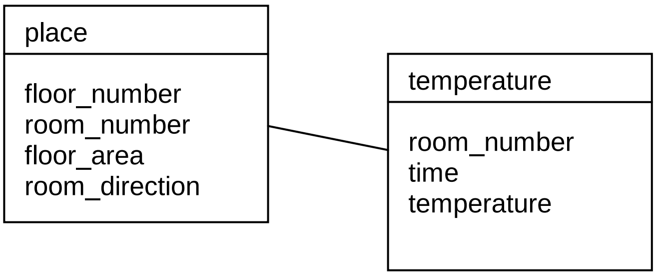


Figure 3.9. Dimensional data model: some redundancy.

Here the floor table and the room table have been merged. This means that the floor_area will be written in all rows. This is redundant as the floor_area is the same for all rooms on a floor. However, for each measurement in the temperature table one needs only to look up data in a single table to find room data as well as floor data. The overall performance of the database benefit from a redundancy based model.

Of course a complete denormalization is possible resulting in a single table:

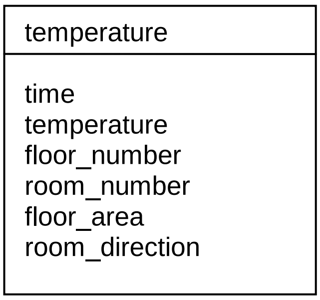


Figure 3.10. Complete denormalization: maximum redundancy.

This is the situation in a spreadsheet. It would usually not be used in a database.

In our database, the data is organized in star schemas. The following figure illustrates the star schema containing the tac data (the data from the building management system).

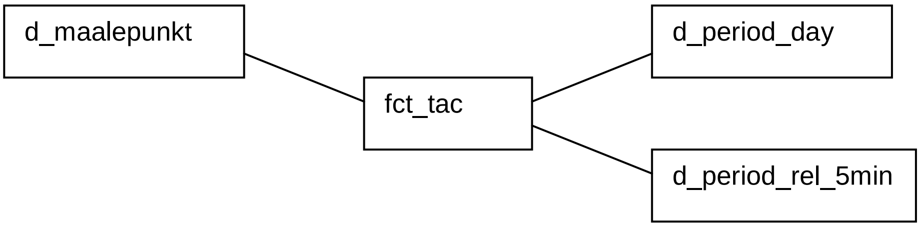


Figure 3.11. Star schema. A fact table surrounded by a number of dimension tables.

Now it becomes more obvious why it is called a star schema. The tables are arranged around a central table. The central table is the fact table, which contains transaction data – in our case measurements. The dimension tables are around it and contain descriptive data. Here we have two time dimensions and a measurement type dimension. Typically the dimensions have many columns but relatively few rows, whereas the fact table is narrow with few columns but with a very large number of rows.

In a star schema the tables are usually linked by means of surrogate keys, i.e. one id-field per dimension. In the tac star schema this means three id's. The id is typically an integer. It is very convenient though, in the case of time dimensions, to use numbers, which can be interpreted directly. In this way it is not necessary to look up a date or a time in the dimensions, they can be interpreted from the id (cf. below).

The fields of the tables are as follows:

d_maalepunkt: A row represents a measurement point, i.e. a time series for a measurement which may also be a set point.

d_maalepunkt	
id_maalepunkt	Surrogate key. Id with no business information.
maalepunkt_navn	Name of the timeseries
anlaeg	System (cooling, heating, floor heating etc.)
anlaeg_besk	Description of system
maalepunkt	Type of measurement
maalepunkt_besk	Description of the type of measurement
enhed	Unit (°C, %, 0/1 etc.)
SET_MAAL	Indicates if it is a set value or a measurement
rumzone	IRR### where ### is the zone number
zonenr	Zone number (three digits)
delbygning	Sub-building, indicates the section of the building
etage	Floor
facadeplacering	Front type of zone (outer, towards atrium or internal)
retning	Compass direction of front
areal	Estimated area of zone in arbitrary unit
sort	Sorting number, lists the zones in walking order

Table 3.1. Measurement point (parameter) dimension. Contains descriptive information on each measuring point, i.e. each time series.

d_period_day: A row represents a date, i.e. a specific day in the calendar. The dimension was populated by means of a stored procedure.

There is a surrogate key as well as a date-like key. The latter is preferable in use, because it makes it possible to conveniently query and populate the fact table without the need to make a look-up in the dimension table.

The table has many fields, which are useful for reporting. Note that some fields are relative, e.g. *month,* which is cyclic, whereas other are absolute, e.g. *yearmonth*.

d_period_rel_5min: The time dimension is used to indicate the time of the day to which the measurement relates. As indicated in the table name the resolution of this dimension is five minutes. This means that each row in the table identifies a time slot of five minutes by means of the start time of the interval. Example: 224000 identifies the period beginning at 22:40:00 and ending at 22:45:00.

The *id_klok* is an integer, and it is time-like. The example just mentioned, 224000, is an id. Because it is a number, it does not show preceding zeroes. Thus 20500 means 02:05:00. To enhance the use of dates and time variables for reporting, a field including preceding zeros is created; its name is klokk. *time* is a similar string showing the hour only. For all 12 rows representing the intervals within an hour this field has the same value. The field *heltime* is a flag indicating if the row is representing the beginning of the hour (1) or not (0).

d_period_day	
id_period	Surrogate key
id_period2	Date-like key (number, YYYYMMDD)
year	Year part of date (number, 4 digits)
quarter	Quarter (number 1-4)
month	Month part of date (number, 1-2 digits)
day	Day of month (number, 1-31)
date	Date (date)
week	Week number (number 1-52)
week_0_53	Week number (number, 1-53), used in Denmark
yearmonth	Absolute year-month (text, YYYY-MM)
year_week	Absolute year-week (text, YYYY-WW)
month_name_en	Name of month, English
day_name_en	Name of day, English
month_name_da	Name of month, Danish
day_name_da	Name of day, Danish
last_day	Date of the last day of the month of the day
last_day_fl	Flags if last day of month (number, 0-1)
days_in_month	Number of days in month of the day
day_of_week_en	Day number of week, English (number 1-7)
day_of_week_da	Day number of week, Danish (number 1-7)

Table 3.2. Period dimension (Day). Identifies all data (Year-Month-Day).

d_period_rel_5min	
id_klok	Time-like number (number, HHMMSS, 24 hour/day, no preceding zeroes)
klok	String with time (text, HHMMSS, 24 hours, incl. preceding zeroes)
time	String with hour part of time (text, HH0000, 23 hours, incl. preceding zeroes)
heltime	Flags if row represents the first part of the hour (number, 0-1)

Table 3.3. Period dimension, relative (5 min). Identifies each 5 minutes interval of any day (Hour-5min).

fct_tac	
id_maalepunkt	id determined from d_maalepunkt
id_dato	id constructed from timestamp of measurement
id_klok	id constructed from timestamp of measurement (measurement time truncated to 5 min.)
maalepunkt_navn	Is included only because it was convenient for loading the massive amounts of measurement data without the need to make a join with the dimension table. The id_maalepunkt was actually populated after load of this field.
vaerdi	Measurement value (number)

Table 3.4. tac fact table. Contains all measurements provided by tac.

fct_tac: The tac fact table contains all measurement data provided by t.a.c. i.e. all measurements from the BMS system. Usually the fact table contains the id's and the value only, but in this case the name of the time series was included for data loading convenience.

Fact tables with identical structure exist for the measurements provided from DONG Energy (fct_dong) and the autonomic data loggers (fct_ik_log)

3.2.4 Populating tables

The setup for loading data used in this project is a pilot project setup. The aim was to design and populate a database applicable for the purpose of the project. In a production environment the process has to be automated.

Collecting and generating data for dimensions
The measurement type dimension, *d_maalepunkt*, was populated with data obtained from t.a.c and derived from maps of the building.

From the measurements a selection of all measurement types present was made. Information from t.a.c. with short descriptions of the timeseries was merged with this extract. Furthermore, from maps window-direction and approximate area of each room was obtained and added to the dimension.

The process was done ‘by hand’. A lot of time consuming work on small details in text files and mapping of the building was necessary. The character of the data makes it necessary to do so, and it is hardly possibly to automate the process to any degree.

The period dimensions, d_period_day and d_period_rel_5min, are much simpler to populate. This can be done by scripts, cf. Appendix 1.

Extracting and loading data to the fact tables
The following figure indicates the setup used in this project.

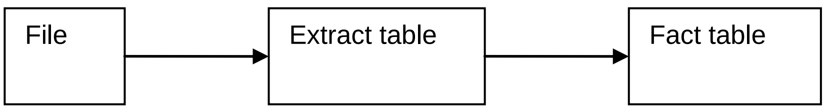


Figure 3.12. Data flow of measurement data.

The logged data were received from tac as text files, which were zipped and send by email. The files were processed as follows:

Download files	The zipped data files attached to the email were downloaded.
Unzip	The data files were unzipped. There is one file per day containing all time series from t.a.c.
Encode	The text files were encoded (with Smultron) to cope correctly with Danish letters.
Load to extract table	MySQL’s file loader is used to load data from a text file

	to a database table. The data are simply read, they are not manipulated in this step.
Load of data to the fact table	Here the id's for the dimensions are determined and the data are loaded to the fact table.

Table 3.5. Process for loading data from tac.

This procedure was developed and used in a pilot environment. In the following section suggestions for a production setup are made.

3.2.5 Suggestions

Data model
In this project two period dimensions were used representing day level and five minutes level. Because the id's were date and time like, the id's themselves could be used in simple reporting (Excel pivot diagrams), where it was easy to study e.g. weekly and daily variation independently.

When using the database for reporting in e.g. R, data is queried and used in native format. In that case there are no benefits in having the date and time periods separated in the present way.

An alternative would be to use an hour period rather than a date period, i.e. a row would not refer to a specific day in a specific year but to a specific hour of a specific day in a specific year. The relative period dimension could define the part of the hour, i.e. in this case the five minutes interval. This dimension would be very small, only 12 rows, and it could be merged into the other period dimension leaving only one period dimension having rows defining specific five minutes intervals. This would probably be the best solution.

The reason not to choose this one could be the question of performance. On low resource systems it might lower performance, if the dimension tables are unnecessarily large.

The reason why it is better to have an hour dimension rather than a day dimension is, that it is much simpler to handle daylight saving time.

Suggestion: Merge the period dimensions to one dimension.

Loading data
In this project the data was provided and loaded by means of manual procedures. For instance: An employee of t.a.c. produced the data files, zipped them, and sent them by mail. They were received, unzipped, encoded and saved as text files. These were loaded to extract tables from where the data was loaded to the fact table.

In a production environment, the setup would be much different. There would be no manual procedures. To get there another method of getting data from source to database must be used. There are different possibilities.

Suggestion: In future projects data should be exchanged by means of FTP file transfer.

The files should be automatically generated by the data provider. A script may be scheduled or run manually, but it should be a script, which actually generates the data files and place them in the appropriate ftp-folder.

When data is received a script should copy it to an archive. If the filename does not include a timestamp, it should be added by the script. The original file to be processed should be renamed to a standard name. In that case the MySQL file load script could work with this standard name.

Data transfer	
FTP	FTP (File Transfer Protocol) is a very simple way of moving files around a network of computers, e.g. the Internet. The file is placed in a folder on a computer on a network. The computer can be addressed by other computers on the network, and the file can be manipulated, i.e. copied, moved, deleted etc. Access to files can be controlled by standard procedures for accessing networks. Because the system generating data, e.g. the t.a.c. system, simply writes data to a file in a folder, and data users simply read the file from the folder, the users never get in touch with the source system. The two are completely disconnected.
ODBC	ODBC (Open DataBase Connectivity) is a standard interface to relational databases. It makes it possible to send a query, i.e. an SQL-script, to the database and receive the query result back. Though it is an effective method for transferring data from one database to another, it is usually not recommended. If the data provider and the data receiver are two different legal subjects, the data provider would usually not allow the foreign receiver to get direct access to the production database. If, however, the two databases are both owned by the user, an ODBC solution would usually be the fastest to implement and use.
Queues	In a Queue system the data provider writes data to a queue, while data users subscribe to queues. This is done through standard interfaces. The method is used in large organisations and has many advantages, such as automatically keeping track of who got what and when. But it requires special software, much setup and would hardly be of interest to projects like this.
Web services	Webservices is an interface to support interoperable machine-to-machine interaction through a network, e.g. querying data on the Internet. However, they are usually not designed for massive data transfer and are thus not necessarily a feasible choice for reporting purposes.

Table 3.6.Common data transfer methods.

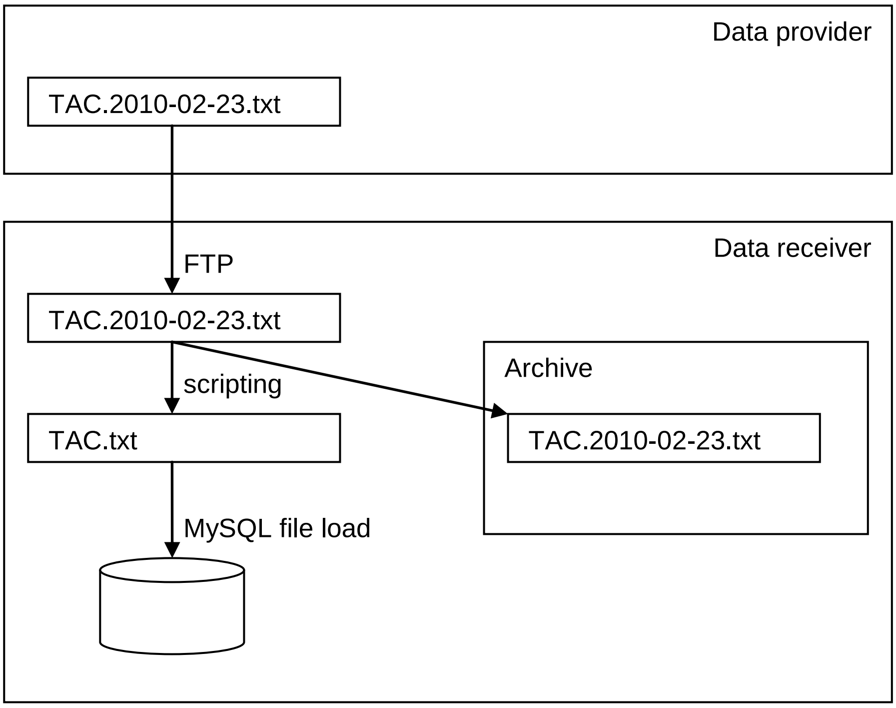


Figure 3.13. Data load process in a production environment.

The scripting could be DOS (bat-files) on Windows or e.g. bash shell scripts in Mac OSX and Linux.

The process could be scheduled so that the ftp-server is polled every day or every hour (or every tenth second as required).

Data integration
When time series data is loaded from the extract tables to the fact tables it should be converted to standard time reference, preferably UTC+1 (UTC: Universal Time, Coordinated – practically the same as Greenwich Mean Time), i.e. normal time in Denmark. By means of the period dimension the CET/CEST timestamps (Central European Time (=UTC+1) / Central European Summer Time (=UTC+2)) can be easily derived. Note that CET/CEST is not completely defining a timestamp: In the fall when returning from summer time to winter time, the day has 25 hours of which two are from 02:00 to 03:00. To completely identify this hour a flag is needed to tell if it is summer time or winter time.

Setting up a platform
A platform for reporting could be based on a multi-server setup:

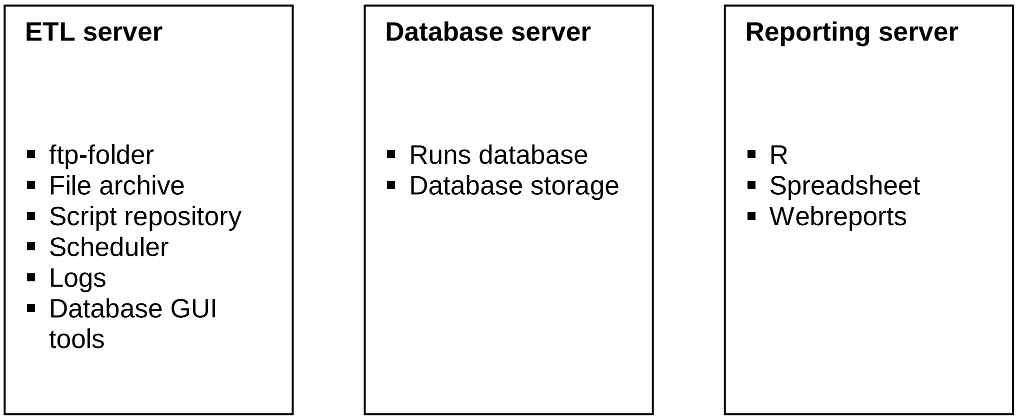


Figure 3.14. Reporting platform architecture.

The database server is dedicated to run the MySQL engine. It should not be accessed directly but only through one of the two other servers.

The ETL server is the back-end. Here data is received from the data providers, transformed and loaded to the database. The data files are archived to make it possible to recreate the database or e.g. load to another data model.

The reporting server is the front end, where the users get access to data. In our case this could run the R-program.

Separating functionality on different (physical) serves increases performance, which is important in reporting systems, because the user should not be required to wait long for query results.

There should be remote access to the ETL-server and the Reporting server. It might be web based, but, for instance, in Windows based systems Remote Desktop is a very convenient way to access the servers.

With remote access it is not necessary to install software on the local computer – e.g. the pc of the user. This is highly preferable to avoid problems with maintenance, software versions etc.

Such a setup would be applicable for users who are somewhat technically skilled. For a user with no required technical skills the data should be more easily accessible. A number of reporting tools are available, e.g. Targit, Business Objects and Cognos, just to mention a few. Such tools are hardly neither necessary nor convenient in an environment like the present, where a more complex software – R – is used for reporting – see Appendix 6 and 7.

4. Indoor environment

Objective measurements of physical parameters in the building and subjective responses from the occupants were used to evaluate and classify the indoor environment conditions in the building. The objective measurements comprised long-term recording of air temperature, air humidity, and CO_2 concentration in 13 selected locations and short-term measurement of air and operative temperatures, and air velocity at representative locations and on two occasions. The subjective responses were obtained from two separate internet based questionnaires.

4.1 Thermal climate

Several standards provide guidelines for assessment of the indoor environment (DSF 3033-2009, DS 474 - 1995, ASHRAE 55-2004, ISO 7730-2005, CEN CR 1752-1998, CEN EN 15251-2007). A common approach of the standards is to define conditions in which a specified fraction of the occupants will find the environment acceptable, and the newest standards attempt to categorize the indoor environment according to its quality.

General and local thermal discomfort

Thermal dissatisfaction may be caused by a too warm or too cool overall thermal sensation. But even for a person who is thermally neutral for the body as a whole, thermal dissatisfaction may be the result of unwanted cooling or heating of local body parts (thermal asymmetry). Separate indices exist for the assessment of the different types of local thermal discomfort.

The indices Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) can be used to assess overall thermal comfort in a wide range of buildings and vehicles with different HVAC systems as well as for different combinations of activity, clothing habits and environmental parameters. The indices are widely used for the evaluation and design of indoor thermal environments. The PMV can be determined when the personal parameters metabolic rate and the clothing insulation are estimated and the environmental parameters air temperature, mean radiant temperature, relative air velocity and air humidity are measured or estimated.

The PMV integrates the effect on the body's thermal balance of the two personal parameters and the four environmental parameters, and predicts the mean thermal sensation on a 7-point thermal sensation scale (Figure 4.1).

The PPD index predicts the number of people likely to feel uncomfortably warm or cool, i.e. those voting hot (+3), warm (+2), cool (-2) or cold (-3) on the 7-point thermal sensation scale. Typically, a 10% dissatisfaction criterion for whole-body thermal comfort is used for the determination of acceptable thermal conditions (ISO 7730-2005, ASHRAE 55-2004). This corresponds to a PMV in the range -0.5 to +0.5. It should be noted that the minimum attainable PPD is 5%, even in spite of a neutral thermal sensation (PMV = 0).

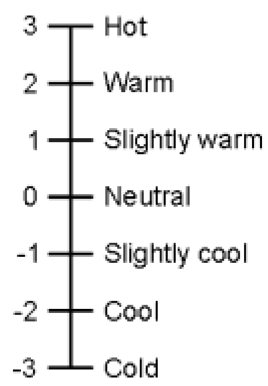


Figure 4.1. 7-point thermal sensation scale corresponding with the PMV index.

Also, local thermal discomfort due to draught, vertical temperature gradient, radiant asymmetry, or warm or cold floors may cause occupants to find the thermal conditions unacceptable. The most common cause of complaint is draught, which is defined as an unwanted, local cooling caused by air movement. Criteria to assess local thermal discomfort are given in ISO 7730-2005 and ASHRAE 55-2004 and are reproduced here in table 4.1.

Category	Thermal state of the body as a whole		Local discomfort			
	Predicted Percent Dissatisfied PPD %	Predicted Mean Vote PMV	Percent dissatisfied due to draught DR %	Percent dissatisfied due to vertical air temperature difference %	Percent dissatisfied due to warm or cool floor %	Percent dissatisfied due to radiant asymmetry %
A	< 6	-0.2<PMV<+0.2	< 10	< 3	< 10	< 5
B	< 10	-0.5<PMV<+0.5	< 20	< 5	< 10	< 5
C	< 15	-0.7<PMV<+0.7	< 30	< 10	< 15	< 10

Table 4.1. Three categories of thermal environment (from ISO 7730-2005).

Each quality category prescribes a maximum percentage dissatisfied for the body as a whole (PPD) and for each of the four types of local discomfort.

Recently, a new Danish standard was proposed for the labeling of indoor climate quality (DSF 3033-2009). Currently, the standard is in a hearing phase prior to being published (as of July 2009). The new standard suggests intervals and quality classes for operative temperature and air velocity during summer and winter that as shown in table 4.2.

Parameter	Season	Quality class				
		A	B	C	D	E
Operative temperature (ºC)	Summer	24.5±1.0*	24.5±1.0	24.5±1.5	24.5±2.5	No limits
	Winter	22.0±1.5*	22.0±1.5	22.0±2.0	22.0±2.5	No limits
Air velocity (m/s)	Summer	0.18	0.18	0.22	0.25	>0.25
	Winter	0.15	0.15	0.18	0.21	>0.21

Table 4.2. Thermal indoor climate quality classes and corresponding parameter intervals. Adopted from DSF 3033 (2009).
*Individual control should be an option

The DSF 3033 (2009) quality classes are characterized by:

Class A: The very good indoor climate. The thermal conditions are comfortable all year round and the building offers good opportunities for individual adjustment. The concentration of unwanted pollutants in the air is low, even when the production rate is higher than normal. Light- and sound conditions are good with satisfactory opportunities for individual adjustment.

Class B: The good indoor climate with very modest health risk and sensory discomfort.

Class C: An indoor climate corresponding to the minimum requirements as specified in the building regulations. This classification is achieved by either fulfilling the requirements in the building regulations at new construction or reconstruction or as the result of measurements/observations. The risk of negative health effects is modest, but sensory discomfort may occur, e.g. as high temperatures on warm days or bad smells.

Class D: An indoor climate poorer than the minimum requirements in the building regulations. The risk of health effects is small, but a considerable fraction of the occupants will experience sensory discomfort due to temperature on warm or cold days or due to smells.

Class E: The poorest of the five quality classes. There is a risk of negative health effects and the safety margin is limited. Considerable sensory discomfort may appear.

Non-steady-state thermal environments
Fluctuations that occur due to factors not under the direct control of the individual occupant (e.g. cycling from thermostatic control) may have a negative effect on comfort. The requirements of table 4.3 apply to these fluctuations. The table specifies the maximum change in operative temperature allowed during a period of time. For any given time period, the most restrictive requirements apply. For example, the operative temperature may not change more than 2.2 ºC during a 1.0 hr period and it also may not change more than 1.1 ºC during any 0.25 hr period within that 1.0 hr period.

Time period	0.25 hr	0.5 hr	1.0 hr	2 hr	4 hr
Maximum operative temperature change allowed	1.1ºC	1.7ºC	2.2ºC	2.8ºC	3.3ºC

Table 4.3. Limits on temperature drifts and ramps (from ASHRAE 55-2004).

Long-term evaluation of indoor temperatures
To evaluate the comfort conditions over time (season, year) a summation of the measured temperature can be used to calculate the number or % of hours the operative temperature is outside a specified range during the time the building is occupied (ISO 7730-2005). CEN EN 15251-2006 recommends evaluation of the time during occupancy when the measured temperature falls in the ranges shown in Table 4.4.

Category	Winter temperature range (ºC)	Summer temperature range (ºC)
I – high level of expectation	21 - 23	23.5 – 25.5
II – normal level of expectation	20 - 24	23 – 26
III – acceptable, moderate level of expectation	19 - 25	22 - 27
IV – values outside the criteria for the above categories		

Table 4.4. Temperature ranges for evaluation of the long-term measurements of indoor temperature in offices (from CEN EN 15251-2006).

Also, DS 474 recommends that the operative temperature during the time of occupancy shall not exceed 26ºC for more than 100 hours and 27ºC for more than 25 hours during a typical year.

Air quality
No common standard index for the indoor air quality exists and the indoor air quality is often expressed as the required level of ventilation or in terms of the CO_2 concentration. It is generally accepted that the indoor air quality is influenced by emissions from the occupants and their activities (bioeffluents, smoking), from the building and furnishing, and from the HVAC system itself. The latter two sources are usually called the building components. The required ventilation is based on both health and comfort criteria. In most cases, the health criteria will be met by the required ventilation for comfort (perceived air quality, odour, irritation).

To assess the air quality in an office building, DSF 3033 (2009) suggests evaluation of several parameters including air change rate and the concentrations of CO_2, radon, formaldehyde and particles. In the current study, in which the measurements were planned and completed prior to the publication of the draft standard, only the CO_2 concentration will be used to assess the level of ventilation according to table 4.5.

Values	Class				
	A	B	C	D	E
CO_2 (ppm)	600	800	1000	1200	>1200

Table 4.5. Quality categories corresponding to the limits of the CO_2 concentration (from DS 3030 (2009) for offices).

4.2 Measurement methods

Measurements comprised four elements:

- Continuous, long-term measurement of air temperature, air humidity and CO_2 concentration in 13 selected locations from the 5th February 2008 to the 28th October 2008.
- Detailed spot measurement of air temperature, operative temperature and air velocity on two selected days, 6th March 2008 and 11th September 2008.
- A survey of the occupants' general perception of the indoor environment in the building (background survey)
- A survey of the occupants' perception of the indoor environment on the 6th March 2008

Long term measurements
Air temperature and relative humidity were logged every 15 min with small measurement stations comprising a HOBO data logger model U12-012 with built-in temperature and humidity sensors and a Vaisala CO_2 transducer model GMW22. The accuracy of the HOBO loggers were ± 0.4ºC at 25 ºC for temperature and ± 2.5% from 10%-90% RH (www.onsetcomp.com 2009).

Figure 4.2. Measurement station.

The accuracy of the CO_2 transducer was ±2 % of the range ±2% of the reading. One of each device was mounted on a plywood board with the wires gathered on the back of the board – figure 4.2.

Measurement stations were distributed on the ground floor, first floor, second floor, and fourth floor at an approximate height of 0.6-0.8 m above the floor. The location of the loggers on each floor is shown in Figure 4.3.

Figure 4.3. Location of the measurement stations on each floor.

It was attempted to distribute the loggers to represent indoor environment exposures on each floor and in sections at different orientations of the building. The office hotel on the third floor was excluded from the measurement protocol due to its configuration with many non-uniform and independent spaces. The measurement stations are identified by the last four digits of the logger serial number, which is used throughout the following presentation of the measurement results.

Spot measurements
Spot measurements were made on two days (6th March 2008 and 11th September 2008) as close as possible to the occupants and in the vicinity of the measurement stations. Air and operative temperature, relative humidity and air velocity were measured at three heights (0.1 m, 0.6 m and 1.1 m) representing the ankles (draught, vertical air temperature difference), the centre of gravity of the body (overall thermal comfort) and the neck height (draught, vertical air temperature difference). All parameters were measured with a Brüel & Kjær 1213 indoor climate analyzer during a period of at least three minutes.

Background questionnaire
Occupant responses were collected via an internet-based questionnaire focusing on the occupants' general impression of the indoor environment, their perception of different Indoor Environment Quality (IEQ) factors, and the prevalence of symptoms and adverse perceptions, e.g. high temperature, during the previous month. The questionnaire can be seen at https://www.ie.dtu.dk/iaqtub08 (access code: indeklima). By email, the occupants were invited to fill in the questionnaire.

Short questionnaire
Simultaneously with the spot measurements, occupants were invited to complete a shorter questionnaire on their immediate impression of the thermal indoor climate, symptom intensity, intensity of adverse perceptions, and self-assessed performance. Visual Analogue Scales (VAS) were used in these assessments. Figure 4.4 shows an example of such scales. The short questionnaire in its full length can be seen at https://www.ie.dtu.dk/iaqtub08/short (access code: indeklima).

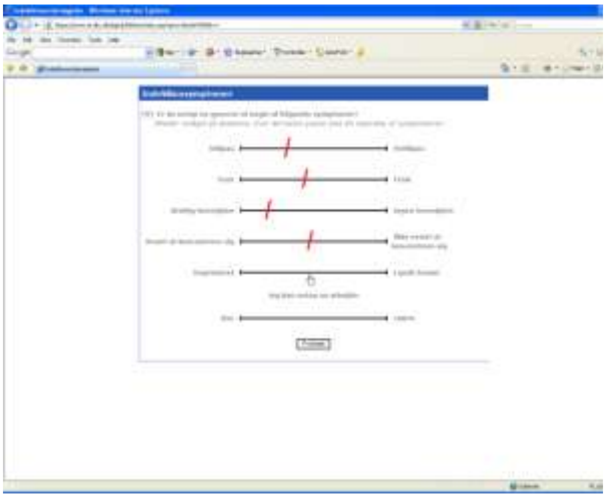


Figure 4.4. Example of a questionnaire page with VAS scales.

This questionnaire was completed during the period when the spot measurements were taken. Originally, the short questionnaire should have been completed on both the 6th March 2008 and 11th September 2008, but due to a mistake at the company with the highest response rate in the first round of measurements, the invitation email for the second round was never sent. Therefore, the short questionnaire was completed only on the 6th March.

4.3 Results

Long-term measurement of temperature and air humidity
For each month in the measurement period and for each measurement station, Appendixes 1 and 2 summarize mean, median, minimum and maximum temperatures and air humidities,

respectively, during the main occupancy period, which was assumed to be from 8:00 – 18:00. Also the standard deviation of the measured temperatures and air humidities within month and measurement station is included in the appendixes.

In general, the mean temperatures deviated only modestly between months from February to October indicating that the climatic system sustained nearly the same temperature regardless of the season and the changes of the outdoor temperature. The largest variation seemed to occur on the second floor in room 324 (facing west), where the monthly mean temperature varied nearly 2ºC from March to June. Some indoor climate standards recommend that the temperature in the occupied zone should be kept in the range 20-24 ºC (winter) and 23-26 ºC (summer) (e.g. DS474-1995). The measured mean temperatures suggest that the temperature during the winter season was near the upper comfort temperature limit, which may result in a too high energy consumption and sub-optimal comfort for occupants wearing heavy winter clothing. At most locations, the standard deviations of the temperature, quantifying the variability within month of the temperature measured at each location, was also very low.

Based on the data in appendix 2.1, Figure 4.5 shows that the monthly maximum temperature increased with the mean temperature indicating that high temperatures may have occurred not only at the instant when the maximum temperature was recorded, but possibly during sustained periods at that particular location and month.

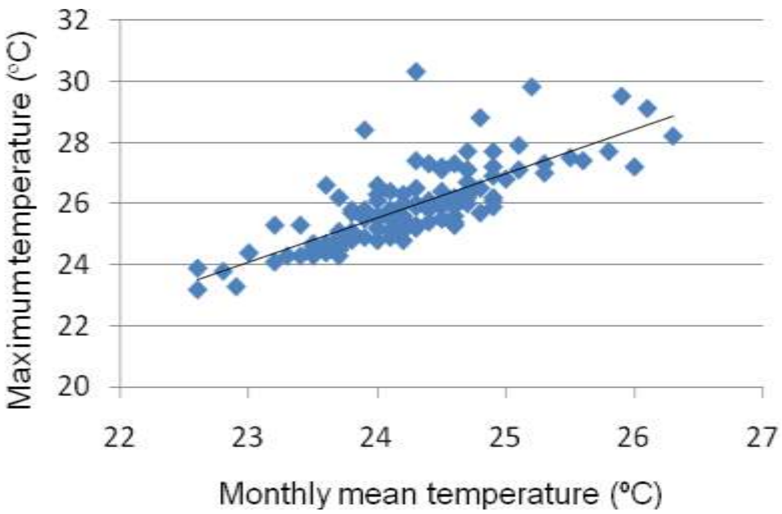


Figure 4.5. Monthly maximum temperature vs. the mean temperature at all measurement locations.

Figure 4.6 shows that there was a relation between the standard deviation of the temperature (std) and the maximum temperature (left), but not between std and the minimum temperature (right). Thus, the largest variability in the temperature also occurred where the highest temperatures were measured, whereas the minimum temperatures were not related with the temperature variability.

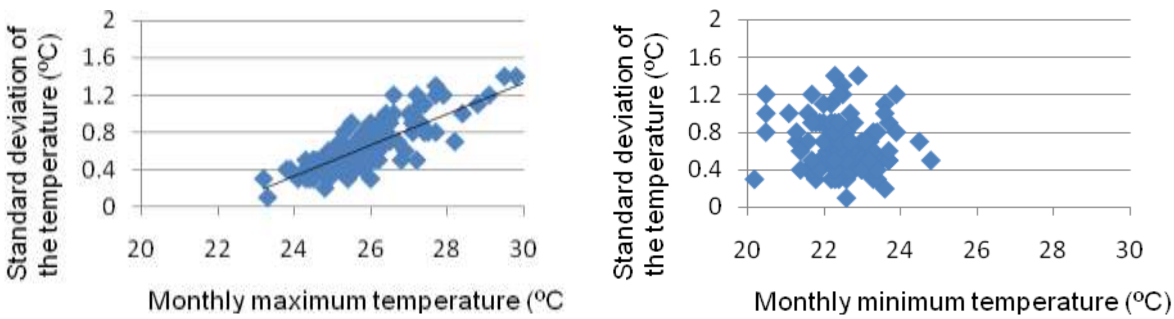


Figure 4.6. Standard deviation of the temperature within month as a function of the monthly maximum temperature (left) and the minimum temperature (right).

According to the temperature ranges recommended in the standards DSF 3033 (2009) and CEN EN 15251 (2006), Figure 4.7 shows the percent of the occupied hours (from 8:00 to 18:00 hrs) during the winter and summer seasons when the hourly mean temperature fulfilled the requirements to quality classes B to E (table 4.2) and with only small deviations to classes I to IV (Table 4.4). The winter season was interpreted as February, March and October and the summer season as the period from April to September (both inclusive). Since temperatures at all measurement locations deviated only modestly between seasons, and since temperatures generally were high and within the recommended summer comfort temperature range, the thermal conditions were ranked higher during the summer season. None of the recordings could be class A, since this quality class required individual control of the temperature (DSF 3033-2009).

Figure 4.7. Percent of hours when the hourly mean of the measured temperature during winter (left) and summer (right) was in the ranges recommended by or DSF 3033 (2009) and CEN EN 15251 (2006) for quality classes B, C, D, E and approximately for the classes I, II, III, and IV, respectively (table 4.2 and table 4.4)

Table 4.6 shows the accumulated number of hours during the measurement period, which included the full summer season, when the temperature exceeded 26ºC and 27ºC (DS 474-1995). Also, the table shows the percent of the occupied hours when the temperature exceeded 26ºC (ISO 7730-2005). The three locations with the highest number of hours with temperatures exceeding the comfort range (3028, 3041, and 3031) were all near the west-facing façade and served by ventilation system 3 (3028 ground floor and 3031 second floor) and system 2 (3041 first floor). Logger 3046 on the second floor also exceeded the recommendation, but this logger was located in the window sill outside the occupied zone and it may have been exposed to direct sunlight. Thus, the most critical location in terms of maintaining a comfortably cool temperature was the offices facing west.

Within the comfort temperature range, air humidity has only a modest effect on the perception of comfort when the activity level is low. However, very low air humidities may result in problems with static electricity or drying of the mucous membranes, particularly in the eye, during prolonged exposure. High humidities may affect the perception of the air quality and result in the air being perceived as stuffy and uncomfortable. Typical guidelines recommend that the air humidity should be in the range 30-70% relative humidity (rh), but the scientific basis for assessing the effect on humans of air humidity is somewhat inconclusive. Appendix 2.2 shows that during the winter months, the measured minimum rh was below the recommended range, but the mean rh, although still below this range, was somewhat higher. As could be expected with limited indoor sources of moisture, air humidity changed mostly with the outdoor climate and reached the highest values during the summer period.

Logger	No. of hours when t > 26ºC	No. of hours when t > 27ºC	Percent of time when t > 26ºC (%)
3028	391	93	25
3041	166	34	9
3034	74	8	4
3033	32	4	2
3029	8	0	0
3031	205	64	11
3036	0	0	0
3037	0	0	0
3038	0	0	0
3039	56	0	3
3040	0	0	0
3042	1	0	0
3046	116	4	9

Table 4.6. Accumulated number of hours during occupancy when the recorded hourly mean temperature was higher than 26ºC and 27ºC (DS 474-1995) and the percent time when the temperature was above 26ºC (ISO 7730 – 2005).

Temperature variations with time

Standards' criteria to temporal temperature variations are based on differences in temperature calculated for 15 min, 30 min and 60 min temperature change, which will be explored here (table 4.3), as well as differences calculated for longer intervals. For all measurement locations, Appendix 2.3 shows the running temperature difference calculated for 15 min lag, 30 min lag, and 60 min lag. As an example, Figure 4.8 shows the temperature variation at location 3031, which is one of the more critical locations in terms of temperature transients. As was the case with the highest temperatures, the largest temperature variation that frequently exceeded the standards' recommendations was observed at locations near the west-facing façade (3028 ground floor, to some extent 3041 on the first floor, and 3031 second floor). At the end of the measurement period in October at location 3046 on the second floor (logger located in window sill at south facing façade) high temperature variation was recorded during some days. At all other locations, the temporal temperature variation was very modest and far below the criteria in table 4.3.

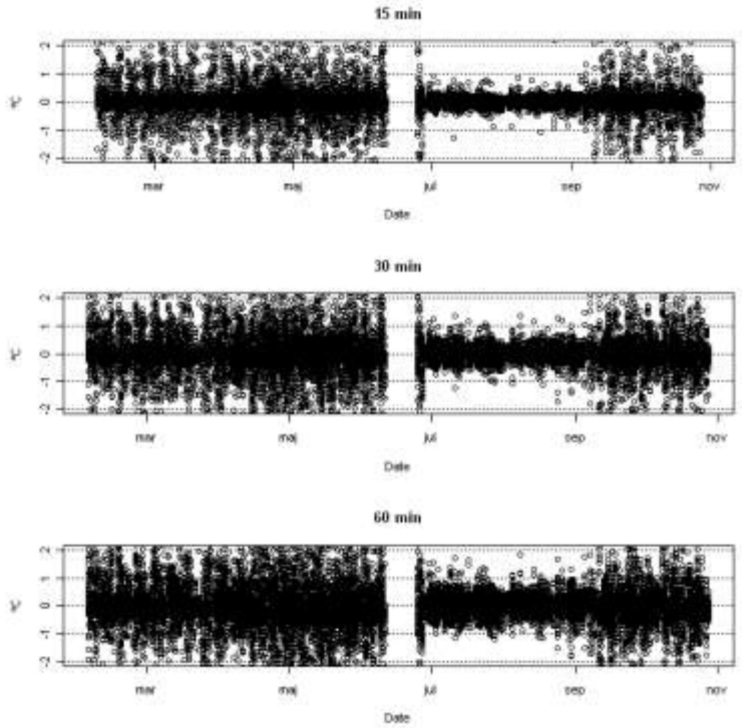


Figure 4.8. Temporal temperature difference determined for measurement location 3031 for 15 min, 30 min, and 60 min lags.

Long-term measurement of the CO_2-concentration

The CO_2 concentration was logged every 15 min together with air temperature and air humidity, but in contrast to the ta and rh measurements, the CO_2 transmitter required an external power supply, which at some locations and during some periods unfortunately was disconnected by cleaning staff or employees. Therefore, the number of recordings of CO_2 varied between 80% to 100% of the total amount of ta/rh data points depending on the location.

As an example, Figure 4.9 shows the diurnal variation during April of the CO_2 concentration measured on the 4th floor in room 531 (logger 3039). The figure shows a clear increase in the concentration during the day followed by a decrease during the night, when the building was unoccupied. A similar pattern was seen at the other measurement locations. During the selected measurement period, the concentration at the selected location was never higher than what is required by the best quality class recommended by DSF 3033 (2009), reproduced here in table 4.5.

Figure 4.10 shows that the percent of occupied hours when the hourly mean CO_2 concentration fulfilled the requirements to quality class A was very high. Just in a few locations and during shorter periods the concentration corresponded to class B and was never lower (corresponding to concentrations above 800 ppm) (DSF 3033 2009). Thus, the supplied airflow rate seemed to be high in relation to the occupant density, although it should be noted that the air quality depends also on other pollution sources present in the building, e.g. the carpets, furniture or the ventilation system itself.

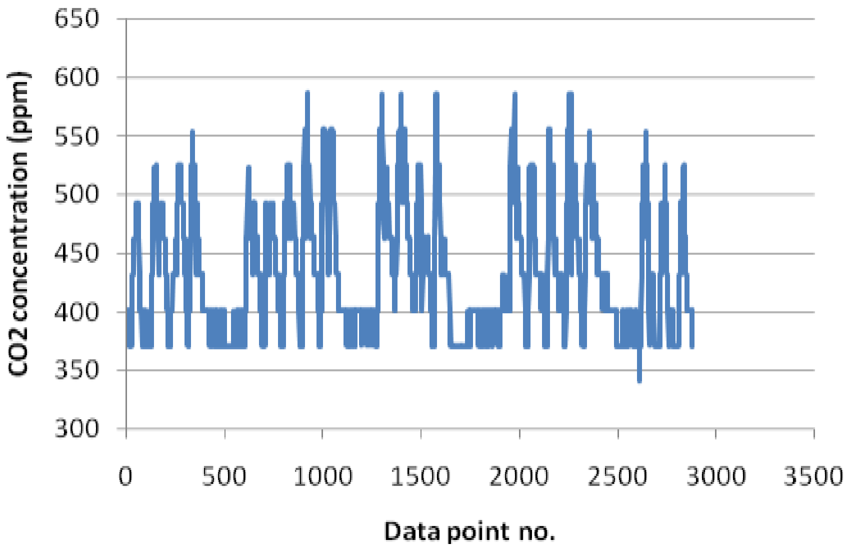


Figure 4.9. Example of the diurnal variation in CO_2 concentration (logger 3039).

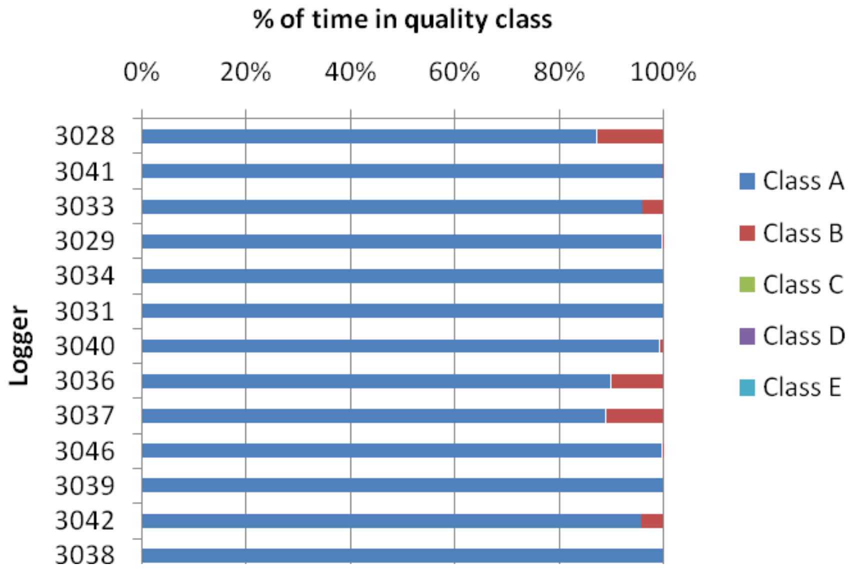


Figure 4.10. Percent of the occupied hours when the hourly mean of the measured CO_2 concentration was in the ranges recommended by DSF 3033 (2009) for quality classes A, B, C, D, and E table 4.5).

Spot measurements

To assess general thermal sensation based on the PMV model and local discomfort due to draught and vertical air temperature difference, spot measurements of air temperature, operative temperature, air velocity, and turbulence intensity were carried out near the locations of the loggers thus representing the exposure in a given zone and floor. Measurements were done on the 6 March 2008 and repeated on the 11 September 2008 and the outdoor temperature on these days was 1.5 ºC and 13.2 ºC, respectively. Appendix 2.4 summarizes all physical measurements, PMV and the draught rating (DR) expressing the percent of the occupants expected to be dissatisfied due to draught. PMV was determined for an average clothing insulation of 0.75 clo (transition between summer=0.5 clo and winter =1 clo) and an activity level corresponding to 1.1 met, typical for office work.

The highest quality class in table 4.1 corresponding to $-0.2 < PMV < 0.2$ is extremely strict and it is currently being discussed whether occupants are at all able to perceive if the thermal indoor climate fulfills class A or class B (Arens et al. 2008). Nevertheless, with the estimated clothing insulation and activity level, most predictions corresponded to class A or class B indicating that the operative temperature on the measurement days was satisfying.

The measured air velocity was generally low and therefore the predicted draught rating was also rather moderate, except in a few locations. Air velocities were measured both directly under and between the air supply units, close to the employee desks, in the perimeter, middle and inner zones near the atrium glass partition, but no systematic pattern was detected that could indicate where the high velocities typically occurred. Fifty percent of the predictions of draught rating corresponded to quality class A (DR < 10%), 42 % to class B (10% > DR < 20%), and 8 % to class C (20% > DR < 30%). The air velocity measurements were carried out on days when the building cooling load presumably was lower than on a hot summer day, when it could be expected that the supply air temperature would be much lower. On such warm days, downdraught from the air terminal devices may cause higher air velocities in some areas. During the study period, however, air temperatures were generally rather high and air velocities low and as a result, the predicted draught rating did not indicate serious draught problems.

At all measurement locations, the operative temperature was almost equal to the air temperature indicating that there was no high intensity radiant sources or cold surfaces that caused thermal asymmetries. Also, the largest measured vertical air temperature difference between head and ankles was 0.4 K, far below the standards' criteria.

Subjective data – background questionnaire

The background questionnaire was completed by 192 occupants (113 females and 80 males); 38 on the ground floor, 124 on the first floor, 14 on the second floor and 16 on the fourth floor.

The main outcome of the questionnaire study was the prevalence of building related symptoms and adverse perceptions. Both prevalences will be compared with statistics obtained in a large and somewhat representative number of Danish office buildings (CIS 2000).

Table 4.7 shows the prevalence of building related symptoms, the prevalence of symptoms regardless of these being building related and the median and 90% percentile for corresponding prevalences in the reference material in the Glostrup questionnaire on which the applied background questionnaire was based (CIS 2000). Symptoms are called building related when the intensity of the symptom is reduced when the occupant leaves the building. The symptom prevalences in table 4.7 correspond to the symptom being present often (weekly) or daily. For example, 41% of the occupants felt lethargy on a weekly or daily basis, while 29% felt lethargy while being in the building, but it improved when they left the building.

The comparable reference material (Glostrup) was recorded in 41 randomly selected buildings equally distributed in Denmark. Around 2/3 of the responses were obtained from women, which was compatible with the current survey. The median indicates that for a certain symptom 50% of the buildings had prevalences below the value indicated in the table, i.e. in 50% of the buildings studied in the Glostrup survey up to 12% of the occupants reported they suffered from lethargy. Likewise, the 90% percentile indicates that 90% of the buildings had prevalences below the value in the table, i.e. in 90% of the studied buildings the prevalence of lethargy was below 19%. As a guideline, the currently observed symptom prevalences shown in table 4.7 should not be above the Glostrup 90% percentile, but if a high indoor environment quality is desired, a value below the Glostrup median should be aimed at (CIS 2000).

The observed prevalences of specific (eyes, nose, throat, skin) and general (lethargy, headache, concentration difficulties) were generally higher than the values in the reference material.

Symptom	Building related prevalence (%)	Prevalence (%)	Glostrup median (%)	Glostrup 90% percentile (%)
Lethargy	29	41	12	19
Heavy head	33	41		
Headache	13	18	11	17
Concentration difficulties	28	29	4	10
Problems focusing	7	10		
Itch or irritation in the eyes	22	26	6	16
Irritated, stuffy or runny nose	19	23	12	16
Hoarse, dry throat	13	13	3	7
Cough	3	6	7	10
Dry, itchy head or skin on the ears	7	14		
Dry, itchy skin on the hands	12	18		
Other*	4	4		

Table 4.7. Prevalence of symptoms that were present weekly or daily during the month prior to completion of the questionnaire.
*"Other" comprises other symptoms with focus on noise and mucous membranes.

Symptoms with the highest prevalence were distributed on the floors as shown in table 4.8.

In particular, occupants on the ground floor and second floor complained of a high prevalence of general symptoms and somewhat lower prevalence of eye and nose symptoms. On the second and fourth floors, the prevalences were based on responses from only 14 and 16 occupants, respectively, and therefore may not represent well all occupants on these floors.

Symptom	Ground floor (%)	First floor (%)	Second floor (%)	Fourth floor (%)
Lethargy	39	29	21	13
Heavy head	53	28	36	25
Concentration diffi-culties	34	35	14	6
Itchy or irritated eyes	8	26	0	6
Irritated, stuffy or runny nose	16	21	50	25

Table 4.8. Distribution on floors of selected, building related symptoms.

Table 4.9 shows the prevalence of adverse perceptions present weekly or daily during a recall period of one month as stated in the question. The occupants completed the questionnaire in early March, and the responses thus represent their impression of the indoor climate in February and early March.

Adverse perception	Prevalence (%)	Glostrup median (%)	Glostrup 90% percentile (%)
High temperature	46	10	20
Varying tempera-ture	56	16	30
Low temperature	31	9	18
Draught	28	15	29
Stuffy air	64	17	27
Dry air	61	23	39
Noise	69	28	42
Lighting	33	10	20

Table 4.9. Prevalence of adverse perceptions present weekly or daily during the previous month.

Even though larger temperature variation was recorded at the west-facing façade, the prevalence of high or varying temperature among occupants in this section of the building was not higher than in the other sections. Complaints of dry air were rather prevalent, but even though measured air humidities periodically were lower than recommended by indoor environment guidelines other factors, such as e.g. irritants in the air may exacerbate the perception of dry air.

The prevalence of almost all adverse perceptions exceeded the 90% percentile in the reference material indicating that the occupants were rather annoyed with the indoor environment. Even though the survey was completed in March, the prevalence of complaints of high temperature was higher than for low temperature. This corresponds well with long-term measurements of temperature, which showed a relatively constant and high temperature level regardless of the season (Figure 4.7). Thus, some adjustment of the indoor temperature with the season may reduce the prevalence of some of the complaints.

The prevalence of the perception of stuffy air was high despite the high ventilation airflow indicating that other sources than humans may have a dominant effect on the indoor air quality, e.g. the building interior or the ventilation system. Also, noise is a prevalent adverse perception, however not uncommon in high-occupancy open-plan offices as found especially on the ground and first floors.

Table 4.10 shows the prevalence of adverse perceptions, but distributed on the individual floors. On the ground floor where the occupant density was rather high, adverse perceptions such as stuffy air, noise, and varying temperature were particularly high. Draught is one of the most frequent causes of complaints in office buildings, but especially on the second and fourth floors, there were only few complaints of draught, possibly because the occupant density and the cooling load may have been low, leading to a higher supply air temperature. However, only few occupants on the second and fourth floor completed the questionnaire.

Adverse perception	Ground floor (%)	First floor (%)	Second floor (%)	Fourth floor (%)
High temperature	63	45	36	25
Varying temperature	74	51	43	56
Low temperature	39	28	36	38
Draught	39	30	14	19
Stuffy air	82	59	50	69
Dry air	66	59	57	63
Noise	79	66	43	75
Lighting	53	25	29	38

Table 4.10. Prevalence of daily or weekly adverse perceptions distributed on floors.

The distribution of the number of responses to the question ”How satisfied are you with the indoor envionment in the building” can be seen in table 4.11..

	Clearly dissatisfied (%)	Just dissatisfied (%)	Just satisfied (%)	Clearly satisfied (%)	Number of responces
Ground floor	54	35	11	0	37
1st	27	37	33	3	123
2nd	23	54	23	0	13
4th	31	31	38	0	16

Table 4.11. Distribution of responses describing the general satisfaction with the indoor environment in the building.

A majority of the occupants were generally dissatisfied with the indoor environment in the building, in particular on the ground floor and first floor where 89% and 64% of the occupants, respectively, were dissatisfied. On the second and fourth floors, the number of responses was too low to be representative.

The occupants also had the opportunity to comment on the indoor environment in the building, and the comments are summarized in Appendix 2.5 (in Danish). Most comments concern the indoor environment on the ground and first floors and only few relate to the second and fourth floors. Generally, comments focus on the temperature being too high, low, or varying during the day, or too much noise in the open-plan offices, particularly from phone conversation, on draught, and to some degree on stuffy and unacceptable indoor air quality. Thus, the comments agreed well with the adverse perceptions with highest prevalence.

Subjective data – short questionnaire

The short questionnaire used VAS scales to assess the intensity of adverse perceptions and symptoms. These scales only have semantic end points and no indications grading the intensity between the end points. Votes cast on VAS scales therefore vary widely between individuals and the scales are used mostly to assess differences in occupant perceptions with repeated exposures and measurements, where each individual can act as his/her own control. As mentioned earlier, the short questionnaire was completed only once and it was therefore not possible to compare perceptions between the measurements carried out in March and those carried out in September. Instead, data from the measurement in March will be presented in a rather condensed form.

The short questionnaire was completed by a total of 111 occupants divided between floors with 23 responses on the ground floor, 70 on the first floor, 6 on the second floor and 11 on the fourth floor (one occupant did not report on which floor he/she was located at).

For each floor, Table 4.12 compares observed and predicted average thermal sensation. Although not perfect, the correspondence between the observed and predicted values was acceptable, which may indicate that the clothing insulation and activity level estimated to predict the PMV were appropriate for the occupants on March 6. Also, the table shows the distribution of the observed thermal sensation votes corresponding to the ISO 7730 (2005) quality classes.

Floor	Observed average thermal sensation (± standard deviation)	N	PMV	Quality classes		
				A (%)	B (%)	C (%)
Ground	-0.4 ± 0.8	23	0.1	45	15	0
1st	-0.1 ± 1.1	70	0.2	41	6	1
2nd	0.3 ± 1.0	6	0	25	0	0
4th	-0.1 ± 0.8	11	0.1	50	10	10

Table 4.12. Observed thermal sensation, PMV calculated with averages of physical measurements on each floor and the distribution of the thermal sensation votes in the ISO 7730 (2005) quality classes.

Table 4.13 shows the percent of the occupants who on March 6 found the general indoor environment as being comfortable and the temperature as being acceptable. On the ground and 1st floors a rather significant percentage of the occupants were not comfortable, whereas the general comfort conditions seemed to be better on the 2nd and 4th floors where the occupant density was lower. However, on these floors the number of responses was too low to represent the total population.

Floor	Comfortable occupants (%)	Occupants finding the temperature acceptable (%)
Ground	61	65
1st	51	65
2nd	83	67
4th	82	73

Table 4.13. Percent of the occupants who found the indoor environment comfortable and who found the temperature as being acceptable.

Table 4.14 shows that particularly on the ground floor the air quality was not perceived as being good. Also, noise was rated to be somewhat high on all floors. The perception of the cleanliness in the offices seemed rather low on the ground floor, but slightly better on the other floors.

Factor	Floor			
	Ground	1st	2nd	4th
Air quality (0: poor - 100: good)	29 ± 18	38 ± 10	40 ± 10	52 ± 26
Lighting (0: too dark - 100: too bright)	44 ± 17	40 ± 18	51 ± 20	42 ± 16
Noise (0: too quiet – 100: too noisy)	66 ± 19	66 ± 19	65 ± 27	64 ± 21
Air humidity (0: air too dry - 100: air too humid)	71 ± 20	71 ± 20	59 ± 10	61 ± 19
Cleanliness (0: dirty - 100: clean)	36 ± 21	43 ± 17	44 ± 22	51 ± 18

Table 4.14. Intensity of adverse perceptions and occupants' perception of the cleaning standard (mean ± std.).

Table 4.15 indicates that the intensity of selected specific symptoms (nose, mouth, skin, eyes) seemed to be lower on the 2nd and 4th floors than on the ground and 1st floors. With the general symptoms there seemed to be no difference in the intensity between the floors. Self-assessed performance was rated rather high on all floors indicating that the employees did not feel the indoor environment impaired their work performance.

4.4 Summary of main findings

In particular during the winter season, the measured temperatures seemed higher than recommended by the standards, which may cause too high energy consumption and sub-optimal thermal comfort. Comments from the occupants also emphasize on too high temperatures. Also, temperatures varied only little between seasons. Adaptation of the system set-points to the season may promote lower energy consumption and improved thermal comfort. Highest temperatures and largest daily temperature variation was measured in offices facing west and served by ventilation system no. 3.

Symptom	Floor			
	Ground	1st	2nd	4th
Nose (0: dry – 100: not dry)	40 ± 28	42 ± 29	56 ± 43	62 ± 30
Mouth (0: dry – 100: not dry)	39 ± 32	50 ± 31	89 ± 19	63 ± 30
Skin (0: dry – 100: not dry)	33 ± 30	33 ± 23	43 ± 33	42 ± 32
Eyes (0: dry – 100: not dry)	34 ± 32	40 ± 28	61 ± 35	60 ± 28
Eyes (0: irritated - 100: not irritated)	34 ± 31	37 ± 28	67 ± 33	61 ± 30
Lethargy (0: tired - 100: rested)	44 ± 26	50 ± 26	55 ± 29	39 ± 25
Headache (0: severe – 100: no)	69 ± 26	77 ± 25	77 ± 31	77 ± 28
Concentration (0: difficult – 100: easy)	58 ± 29	57 ± 29	63 ± 27	64 ± 31
Right now I'm able to work (0% - 100%)	83± 13	81 ± 18	85 ± 15	78 ± 17

Table 4.15. Intensity of selected symptoms and self-assessed performance (mean ± std.).

The CO_2 concentration was low indicating high ventilation airflow rate in relation to the occupant density. However, a high percentage of the occupants found the air quality unacceptable indicating that other sources, such as processes in the building, interior surfaces or the ventilation system itself were dominant sources.

The prevalence among the occupants of symptoms and adverse perceptions was very high as compared with a representative average of Danish office buildings. Dissatisfaction was mostly caused by noise, unacceptable temperatures, and poor air quality.

High temperatures are known to aggravate the intensity of several indoor climate related symptoms and the perception of poor air quality. Better control of the temperature in the building would thus be an obvious means to improve the thermal conditions and the perceived air quality and reduce the prevalence of symptoms. Although the measurements generally did not confirm high air velocities in the building, complaints of discomfort due to draught were rather prevalent. A more detailed study of the airflow pattern near the supply openings may reveal problematic air velocities when the system operates at highest airflow rate and lowest supply air temperature.

5. Visual investigation of the measurements

The main purpose of the project was to investigate the types of mulitparameter sensors which can be generated based on the logged values from the Building Management system (BMS). This will be dealt with in the next chapter. However, another aim was to investigate how the availability of logged time series may enhance the outcome of traditional inspection of a building and installations. This is done in the present chapter.

The visual investigations of more than 1000 data points logged over 14 months is a major task and it is further difficult to explain the findings if the work is not broken down into smaller areas and illustrated only by well chosen examples.

The inspection of the measured data is therefore divided into the following areas:

- selection of two representative one week periods
- comparison with the findings from the previous chapter
- the electricity demand of the building
- the ventilation systems
- the cooling systems
- temperatures in the rooms
- the atrium
- the radiator system
- energy demand versus ambient temperature

The main part of the illustrations in this chapter is generated using the program R – please see Appendix 7.

5.1. Selection of two representative one week periods

Displaying the data for the whole measuring period is beneficial for some purposes – eg in order to show the dependency on the time of the year, but in order to illustrate how the systems function this is not appropriate. Then there is a need for representative shorter periods. It was, therefore, decided to choose one winter week and one summer week – but which weeks? Figure 5.1 shows the measured ambient temperature and the measured global radiation for the whole measuring period.

As seen there are four 7-14 days periods without data in the time series for the ambient temperature – and three outliers. Some problems are also seen in the start of the measuring period. The same holes in the measurements are seen for the global radiation – and unfortunately the measurements of the solar radiation and other parameters stopped during the first part of May 2008.

The BMS system was not prepared to log measurements. This had to be implemented at the start of the project and as there was no facility for automatically export of the logged data, this had to be done by hand. This of course facilitates errors. In spite of missing data - more for some values than others (later it is stated, that over 80% of the room temperatures were logged) – the outcome of this first attempt to log on such a large system is acceptable.

Due to missing data after the beginning of May 2008 it has not been possible to choose a period with higher ambient temperatures than the wished indoor temperature, however, as the building starts to call for cooling at ambient temperatures close to zero degree this is not regarded a major problem. The two chosen periods is February 12-19 and April 30-May 6 both in 2008. The ambient temperature and global radiation for these two periods are shown in figure 5.2.

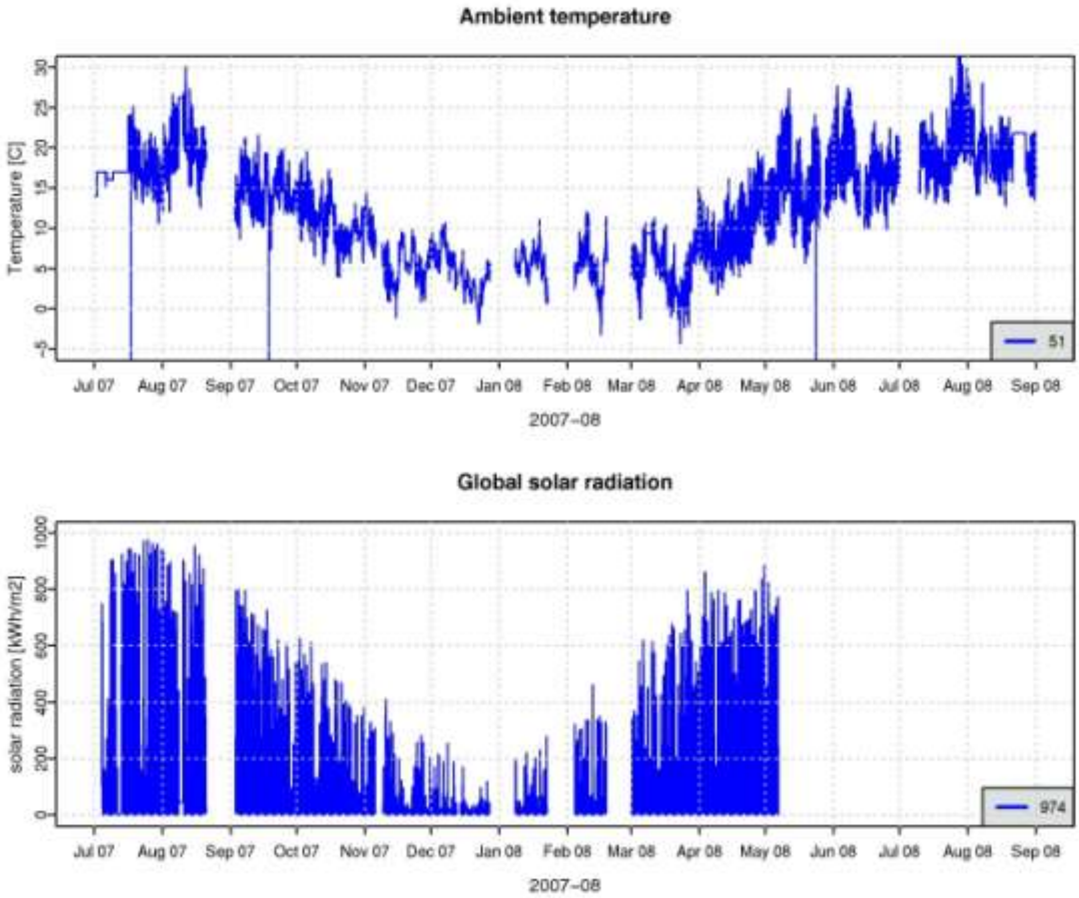


Figure 5.1. Available ambient temperature and global radiation for the measuring period July 1, 2007-August 31, 2008.

The winter period February 12-18 is characterized by low ambient temperatures: -3-12°C and a mix of clear sky, overcast and cloudy conditions.

The spring/summer period April 30-May 6 is characterized by moderate ambient temperatures: 8-22°C and a again a mix of clear sky, overcast and cloudy conditions.

5.2. Comparison with the findings from the previous chapter

In the previous chapter the indoor climate was measured by special purpose sensors where small data loggers - logging temperature, relative humidity and CO_2 - were located close to the users in order to measure the climate the user of the building sense. However, - how do this comply with the indoor climate measured by the BMS system with its temperature sensors in the zones and the mean relative humidity and CO_2 measured in the exhaust air of each ventilation system?

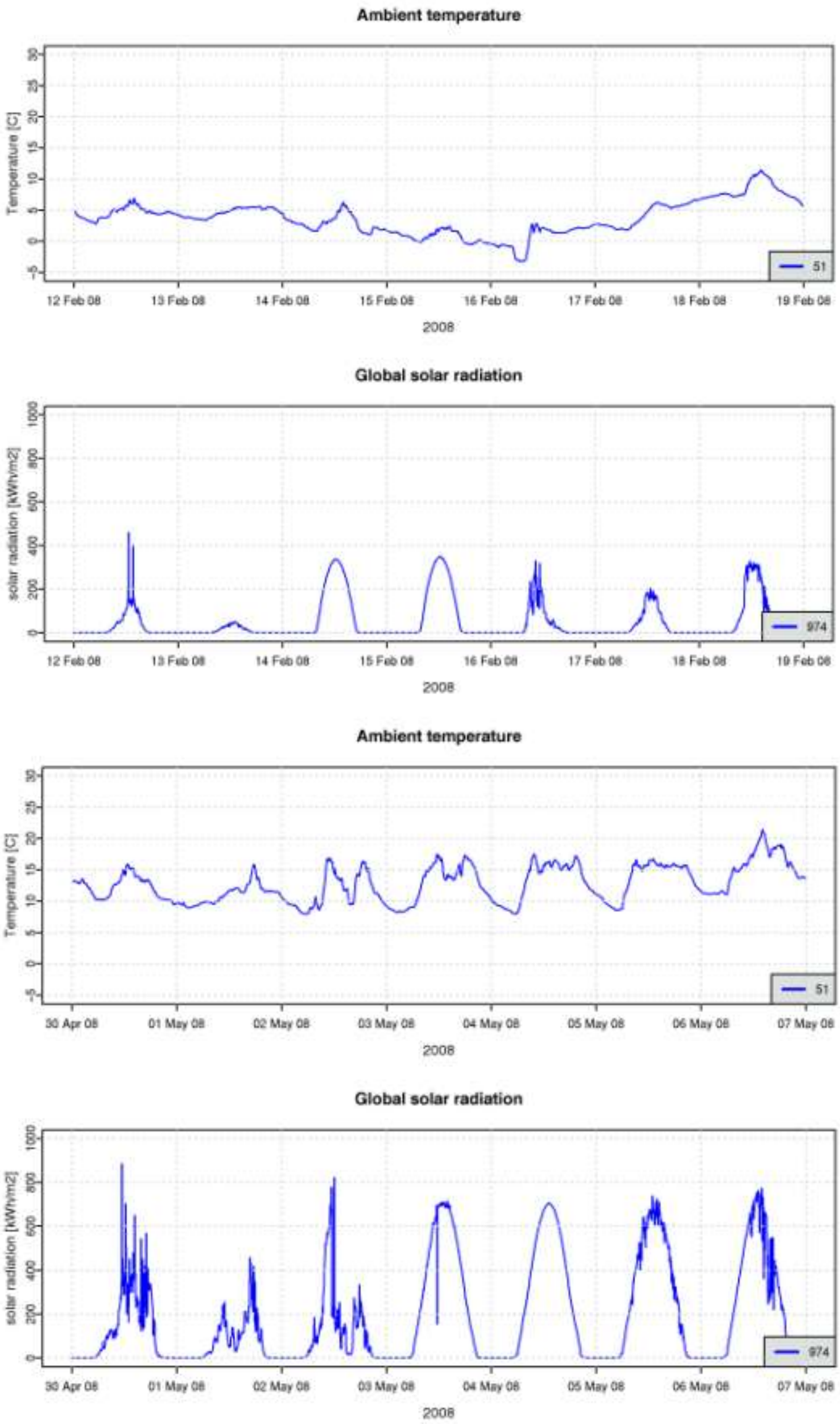


Figure 5.2. Ambient temperature and global radiation for the two chosen periods

Figure 4.3 shows the location of the special purpose indoor climate sensors. In Appendix 3 the measured air temperature of these sensors are compared with the temperature logged by the BMS. In the case where the special purpose sensor is located between two zones the BMS temperature of both surrounding zones is shown. Graphs are shown both for the two selected periods and for the whole period with special purpose climate measurements – February-September 2008. The blue lines in appendix 3 are always the temperature measured by the special purpose indoor climate sensors.

Appendix 3 shows that the difference between the room air temperature measured with the BMS and the indoor climate data loggers is up to ±2 K. This is not bad when considering that the rooms are often open space offices which may easily have a horizontal temperature stratification of ±2 K.

Appendix 3 shows that the difference is negligible for room 316 while the BMS air temperature in mean is 1-2 K lower than the special purpose measured temperature in room 518. For others eg room 322 the BMS temperature drops to a lower level than the special purpose temperature during the day.

A major part of the difference between the two temperature series may be explained by the chosen way of cooling the rooms: cooling baffles. The cooling baffles introduce as seen in figure 2.15 a cold stream of air, which just after leaving the cooling baffle is more or less parallel to the ceiling, but after a short while the cold air starts to drop towards to the floor as shown in figure 5.3.

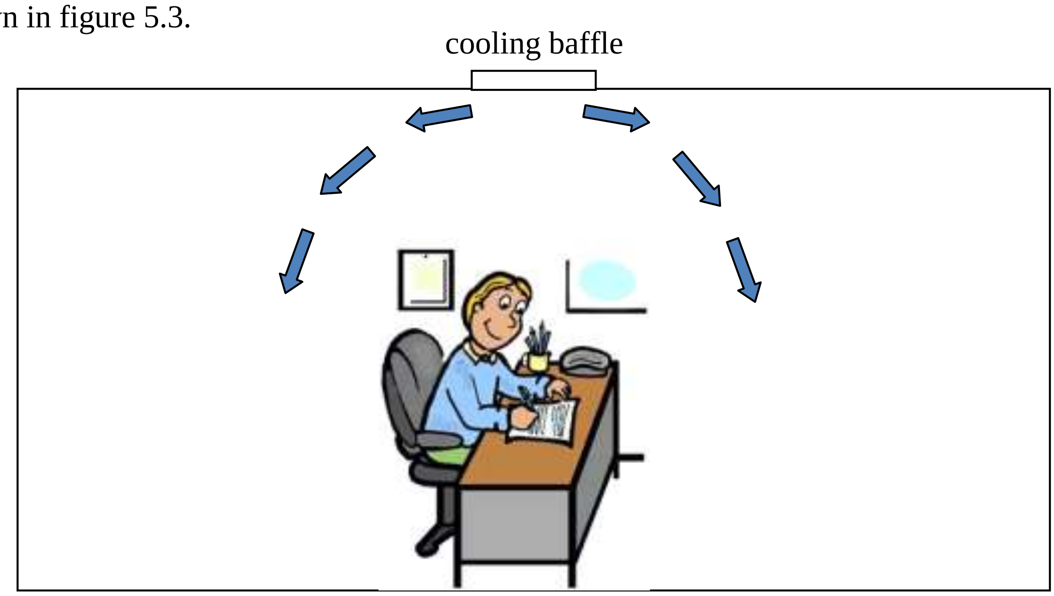


Figure 5.3. The function of the cooling baffles in a room

When visiting the offices it was noticed by inducing smoke that cold air from a cooling baffles was directly hitting the air sensors in eg room 322. Figure 5.4 shows the temperature sensor of room 322. This is also dealt with in section 5.6.

Does this mean that the air temperature does not well represent the air temperature in the rooms? Not necessarily – figure 5.3 shows the right location of a desk compared to the cooling baffles – ie right under the baffles as the cold air stream does not hit the working person.

However the offices are often organized in such a way that people are located right in the air stream from the cooling baffles as seen in figure 5.5.

Figure 5.4. Cold air hitting the temperature sensor directly.

Figure 5.5 Problematic location of a desk.

In other rooms the location of the desks is more appropriate in order to prevent draft. Figure 5.6 shows the arrangement of 4 desks in room 302 right under a cooling baffles where no draft is felt when sitting at the desks. There is in this room no complaint regarding the thermal indoor climate – however there are complaints regarding the daylight conditions as the room is facing the atrium.

Figure 5.6. Arrangement of 4 desks where there is no draft.

The arrangement regarding location of temperature sensor compared to a cooling baffle in room 316 is identical to figure 5.4, but here there is almost no difference between the BMS temperature and the special purpose temperature. An inspection showed that very little air came out of the baffle in room 316 leading to no cold air drop on the temperature sensor in this room.

Based on the investigations of the measured data and visits to the building the following may be concluded:

- cold air from the cooling baffles is often hitting the temperature sensors directly
- people are often located wrongly compared to the location of the cooling baffles. This means that the BMS temperatures may just as well represent the temperature sensed by the users as the indoor climate sensors
- the air flow through the cooling baffles need to be balanced in order to deliver the right air flow volume and thereby obtain the proper cooling capacity but also reduce draft in the occupied zones

5.2.1. Relative humidity and CO_2

The measured CO_2 concentration and relative humidity level were evaluated in chapter 4. They were measured at several locations in the building. However, CO_2 and the relative humidity were also measured in the exhaust of the four ventilation systems Vent1-3 and 7. Figures 5.7 and 5.8 show the results of these measurements for the period February-August 2008. Figure 5.7 shows the measurements in the building while figure 5.8 shows the measurements in the exhaust.

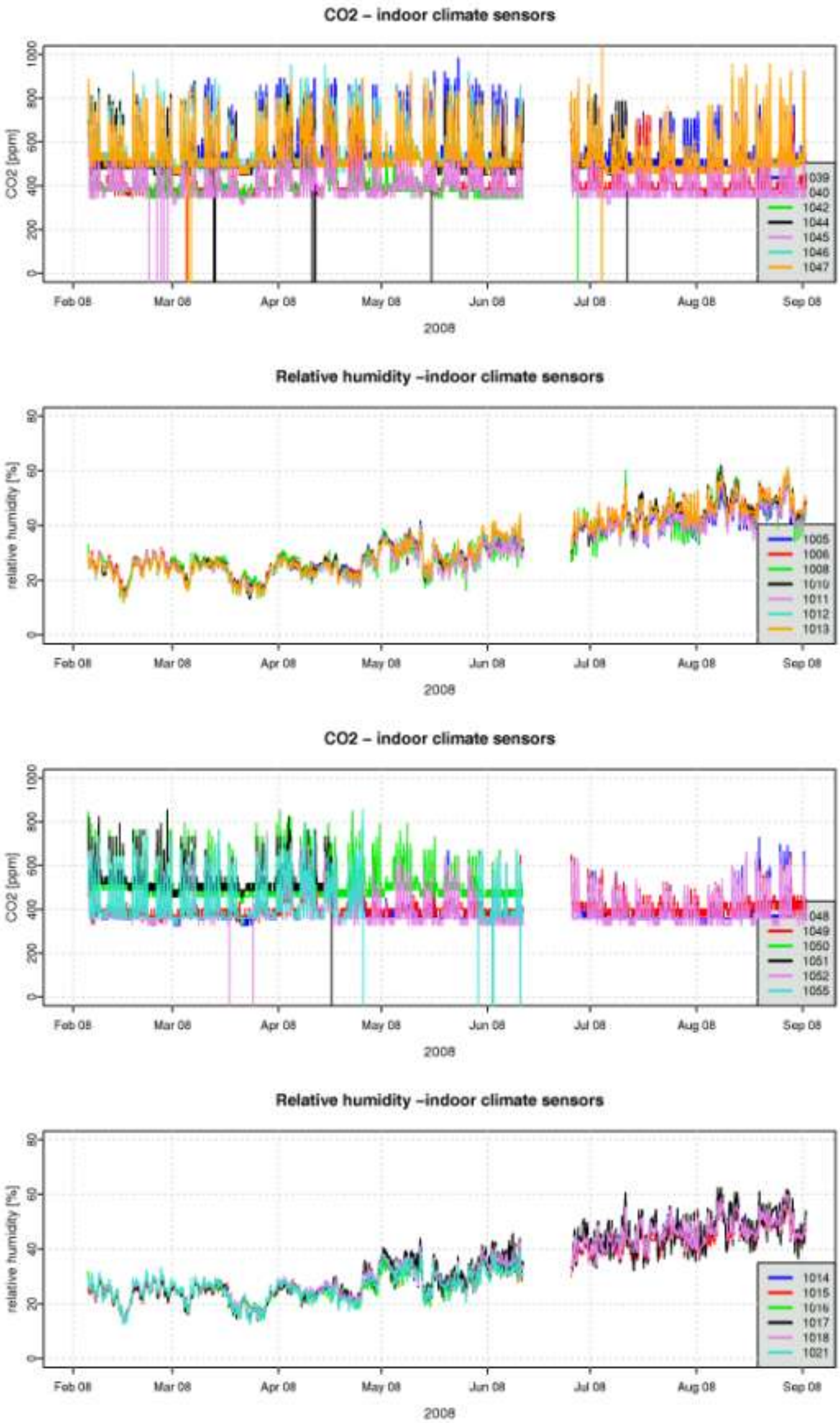


Figure 5.7. CO_2 and relative humidity measured with the special purpose indoor climate sensors.

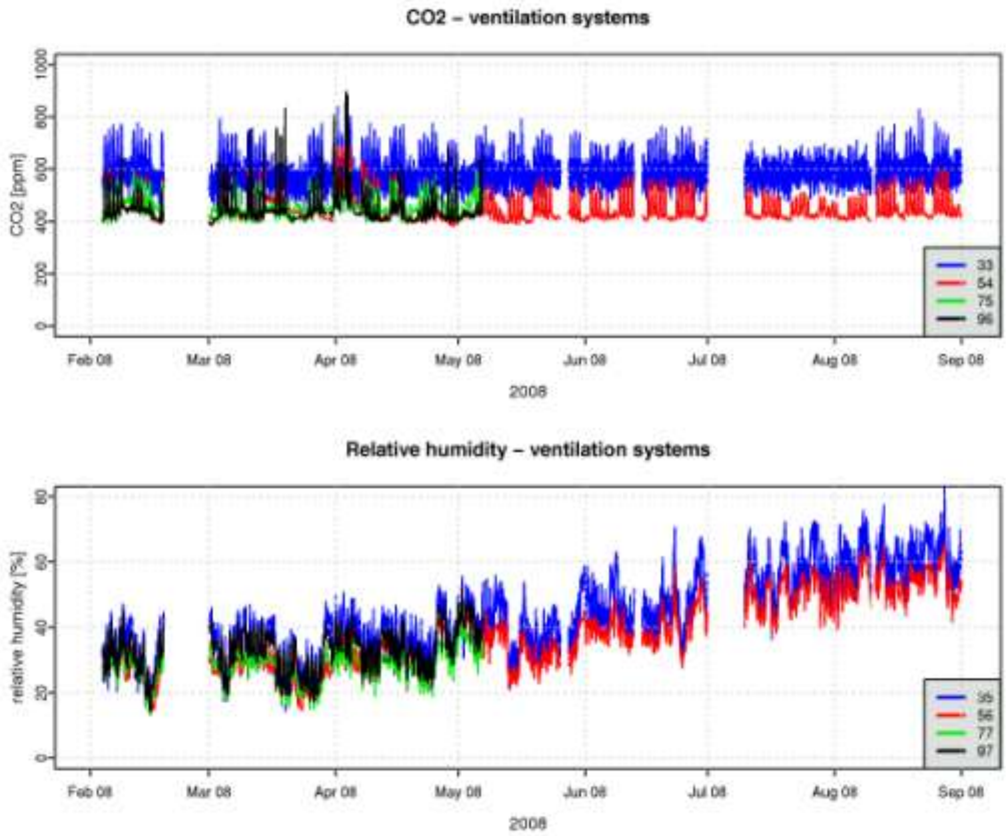


Figure 5.8. CO_2 and relative humidity measured in the exhaust of the four ventilation systems Vent1-3 and 7.

The peak values of CO_2 are slightly lower in the exhaust than in the rooms indicating that the building is less occupied than indicated by the special purpose indoor climate measurements. However, the night values in the exhaust are higher than in the building indicating that the calibration of the sensors may be different. However, both types of measurements show low values for the CO_2.

The measurements of the relative humidity are also very well in agreement except that the peaks in the summer are 10 % point higher in the exhaust. Except for the winter with low ambient temperatures (below 15°C – see figure 5.1) the relative humidity is in the range of the recommendations: 30-70%.

Figures 5.7-8 supports the conclusion drawn in chapter 4: the supplied airflow rate seemed to be high in relation to the occupant density. It is therefore recommended that:

the optimal air flow rates of the ventilation systems Vent1-4 and 7 should be determined and implemented

5.3. The electricity demand of the building

Appendix 4 shows the electricity demand of the building divided into power consumption of the installations in the building and power consumptions of each of the companies occupying the building.

Appendix 4 shows that only the electricity demand of the common installations varies with respect to the time of the year. The power to the installations varies between 100 and 300 kW during working hours while the sum of electrical power to the offices and kitchen is rather stable around 250 kW during daytime.

For the installations the night time energy demand is around 20 kW - 7-10 % during the summer and 16 % of daytime demand during the winter. The low percentage during the summer nights is explained by a high demand for cooling during the day. The 7-16 % “standby power” during the night is low but may be lowered even further if eg the standby demand of cooling system 2 is reduced/eliminated during the night – see section5.5.

The standby demand of the offices varies between around 5 % in the kitchen and 40-50 % in the offices (Dan-Ejendomme, Microsoft 2nd floor and Regus). In the kitchen they turn off most of their equipment when they leave the building. The large standby demand in the offices may be due to a large capacity of servers plus cooling of these. Servers and cooling are running all day and all week. This electricity demand may seem necessary. However the experience of the Danish Electricity Saving Trust (DEST, 2008 and 2009) is that this energy demand may be reduced considerably.

Based on the above it is recommended that:

> an effort is put into reducing the parasitic standby electricity demand in both installations and offices. This will further reduce the cooling demand of the building which will further lead to a reduction in the electricity demand

5.4. The ventilation systems

Table 2.1 gives the dimensioning air flows of the ventilation systems. However, the BMS system does not log the volume air flow rate of the ventilation systems - only a percentage for the fan speed is shown in figure 3.3. The ventilation system Vent1-4 and 7 were therefore inspected in order to determine the actual flow rate of the systems. Table 5.1 shows the result of the inspection. The measured (meas) air flow rates are further compared to the dimensioning flow rates (dim).

System	Fresh air (in)			Exhaust (out)			Ratio between meas in and meas out
	meas	dim	ratio meas/dim	meas	dim	ratio meas/dim	
	m³/h	m³/h	-	m³/h	m³/h	-	-
Vent1	13.784	25.600	0,54	15.784	25.600	0,62	0,87
Vent2	19.512	27.600	0,71	21.158	27.600	0,77	0,92
Vent3	22.620	25.600	0,88	22.032	25.600	0,86	1,03
Vent4	16.543	19.370	0,85	8.803	13.440	0,65	1,88
Vent7	*	3.492	-	3.195	3.492	0.95	-

Table 5.1. Measured and dimensioned air flow rates in the balanced ventilation systems of the building.
* could not be measured.

Table 5.1 and the measured time series show that the actual air flows in the ventilation systems are lower than the dimensioning values of the systems. However, as shown in chapter 4 and section 5.2.1 this seems to be acceptable or maybe even too high with the actual occupancy level.

For Vent3 and 4 the flow of fresh air is higher than the exhaust flow. In Denmark we prefer that the exhaust flow rate is higher than the flow rate of fresh air as this create a slight under pressure in the building which prevent moisture in getting into the constructions. But, if the flow rate of exhaust air from the toilets in the areas serviced by Vent3 is included (2,270 m³/h – table 2.1) there is an under pressure in the areas serviced by Vent3. For Vent4 we also have to consider the exhaust through the kitchen hoods (6,575 m³/h) there is then also a slight under pressure in this area.

In table 5.2 the measured air flow rates divided by the dimensioning air flow rates from table 5.1 are shown together with the fan percentages from the BMS at the same day of the measurements of table 5.1. Except for Vent1 fresh air there is a reasonable agreement with the measured percentage and the BMS values. This means that the measurements from the BMS may be used as an indication of the air flow rate in the ventilation systems – ie the percentage of the dimensioning flow rates.

System	Fresh air		Exhaust	
	meas %	BMS %	meas %	BMS %
Vent1	0,54	0,71	0,62	0,69
Vent2	0,71	0,70	0,77	0,70
Vent3	0,88	0,79	0,86	0,81
Vent4	0,85	0,82	0,65	0,61

Table 5.2. Comparison of fan percentage from table 5.1 with the values from the BMS.

During the inspection of the ventilation systems the pressures around the rotating heat exchangers were measured in order to determine if leakages would be a problem. Further a precision CO_2 measuring instrument was used to measure the CO_2 content in the fresh air stream before and after the rotating heat exchanger to detect if exhaust air was leaking into the fresh air. No serious leakage was detected.

Figures 5.9-14 show graphs of selected values for the ventilation systems Vent1-3 for the two selected periods. Figures 5.15-17 shows values for the two cooling systems, the power of district heating and the global solar radiation as these are necessary in order to understand the function of the ventilation system.

Explanation of the graphs:

Figure 5.9-14:	top graph:	blue curve:	fresh air temperature to CAV
		red curve:	set point of fresh air temperature to CAV
		green curve:	min room air temperature*
		black curve:	max room air temperature*
		purple curve:	mean temperature of the exhaust air from the rooms

	light blue curve:	ambient air temperature
second graph:	blue curve:	% (speed) fresh air fan
	red curve:	% (speed) of exhaust fan
third graph:	blue curve:	% (speed) of rotating heat exchanger
	red curve:	% opening of the heating valve
bottom graph:	blue curve:	% opening of the cooling valve for CAV
	red curve	% opening of the cooling valve for VAV

* max and min room temperature are fictive temperature series logged by the BMS. The BMS log at each time step the room temperature from the room with the highest room temperature and the lowest room temperature. This is shown in Appendix 5 where the room temperatures of the rooms served by Vent3 are shown together with the max (always blue curve) and min (always red curve) room temperatures. The room temperatures in Appendix 5 are arranged according to floor and if they are CAV or VAV ventilated rooms.

Figure 5.15-16:	top graph:	blue curve:	supply water temperature to the ventilation systems from cooling system 1
		red curve:	return water temperature from the ventilation systems to cooling system 1
	second graph:	blue curve:	power to cooling systems 1
	third graph:	blue curve:	supply water temperature to the cooling baffles from cooling system 2
		red curve:	return water temperature from cooling baffles to cooling system 2
	bottom graph:	blue curve:	power to cooling systems 2

It is not easy to obtain a clear picture of the function of the three ventilation systems based on figures 5.9-14 – however, a closer inspection reveals that the pattern of the curves for the three systems is very much alike. As the pattern of ventilation system 3 is most clear and because ventilation system 3 serves the thermally most stressed rooms of the building (see section 5.6) the following investigations are therefore focused on ventilation system 3 – figures 5.13-14.

The investigation is further divided into the two periods – February and May.

5.4.1. Ventilation system 3 – February 2008 – figure 5.13

February 16-17 is a weekend.

The second graph in figure 5.13 shows that the air flow rates of the ventilation system are very constant around 75% of the dimensioning flow rates. The flow rates are a little less constant for ventilation system 2 – figure 5.11. And it is very fluctuating in ventilation system 1 – figure 5.9. The latter should be investigated further.

The third graph in figure 5.13 shows that the heat exchanger wheel is nearly always running at full speed when the ventilation system is on. This is due to the low ambient temperature. The speed of the rotating heat exchanger is only reduced shortly on February 14 and 18.

The opening of the valve for the heating coil in the ventilation system is very fluctuating. This suggests that there is a problem with the regulation of this valve or that the temperature sensor is not located optimally. However, this fluctuation is not seen during the May period (figure

5.14) although the valve often is more open here. The fluctuation of the valve leads to fluctuations in the inlet temperature of the fresh air to the rooms – the blue curve in the top graph. This may lead to discomfort in the rooms. Appendix 2.3 shows that the fluctuation of the room temperature in rooms served by ventilation system 3 (sensors 3028, 3031, 3040 and 3039) in general seems to be somewhat more fluctuating than in the other rooms as shown in in Appendix 2.3. The fluctuation of the opening of the valve may lead to exceeded wear and thereby more maintenance. The fluctuation may also lead to difficulties in keeping a proper cooling of the water from district heating. The resolution of the meter on the district heating is poor (figure 5.17) so it is not possible to see if the fluctuation also lead to fluctuations in the power from the district heating.

The valve for the cooling coil for CAV is always closed (also during the May period and for all ventilation systems) while the valve for VAV is open during a large part of the day during February 12, 13 and 18, but only during a short period on February 14. The valve does not open during February 15. This different pattern over the week is due to the fact, that VAV rooms do not have cooling baffles and are cooled entirely by the fresh air and that these rooms are often meeting rooms with changing cooling load. The operation of the valve is also very fluctuating here. This is not due to changes in the air flow rate – the total air flow rates are as already mentioned very stable. On the other hand the temperatures of the cooling system are also fluctuating – see the top graph of figure 5.15. This will be dealt with in the following section 5.5.

The set point of the temperature of fresh air to the rooms was during working hours 21°C – red curve in the top graph of figure 5.13. Except for the fluctuations due to the fluctuations of the heating valve in the ventilation system the set point was met. The graph further shows that the min room temperature varies between 20 and 22°C while the max temperature varies between 27 and 31°C in spite of the rather low ambient temperature.

Appendix 5 shows the room temperature of the rooms served by ventilation system 3. By investigating figures A5.1-2 in Appendix 5 it is seen that the min temperature is mainly generated by room 455 (value 754 - green line in the bottom graph of figure A5.1) except of two peaks on February 14-15 where room 331, 447 and 533 at different times are the min temperature.

The max temperature is also mainly generated by one room: room 328 (value 454 – light blue line in the third graph in figure A5.2) except for two spikes again on February 14-15 (due to large solar radiation – figure 5.17) where nearly all the rooms in the bottom graph in figure A5.1 are the max temperature: rooms 455, 456, 457, 458, 459, 460, 461 and 462 gives the max temperature.

The rooms causing the min and max temperatures are shown in figure 5.18. From this figure it is seen that it is - except from room 533 - small rooms which caused the min and max temperature. In figures A5.1-2 it is seen that the mean value of the temperatures is around 24°C. The top graph in figure 5.13 shows that the mean temperature of the exhaust air from all rooms varies between 20 and 26°C. The room temperatures are not very well represented by the min and max temperatures while the exhaust air temperature better represent the mean temperatures in the room served by ventilation system 3.

The air temperature of the rooms in the building will be dealt with further in section5.6.

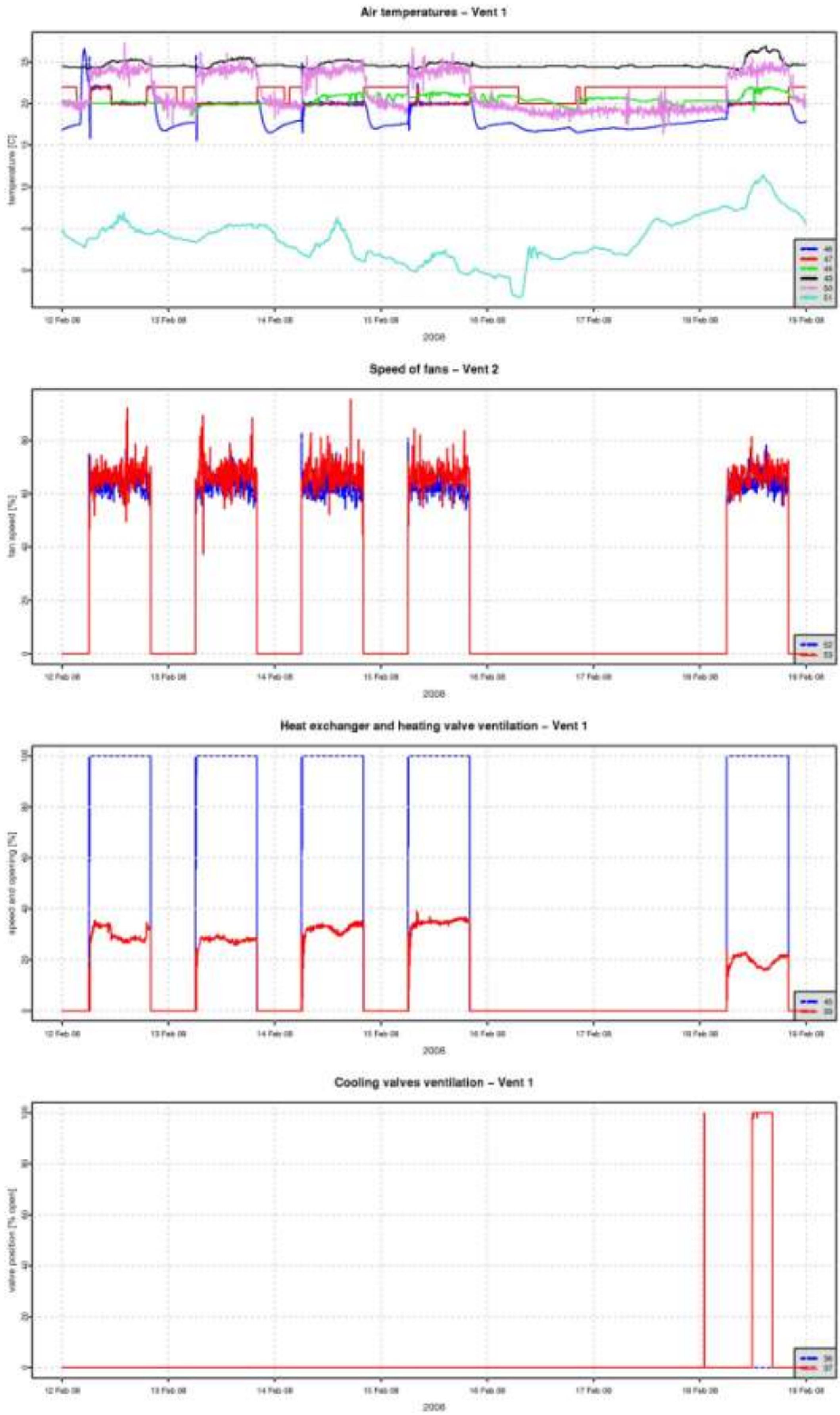


Figure 5.9. Values for Vent 1 – winter period.

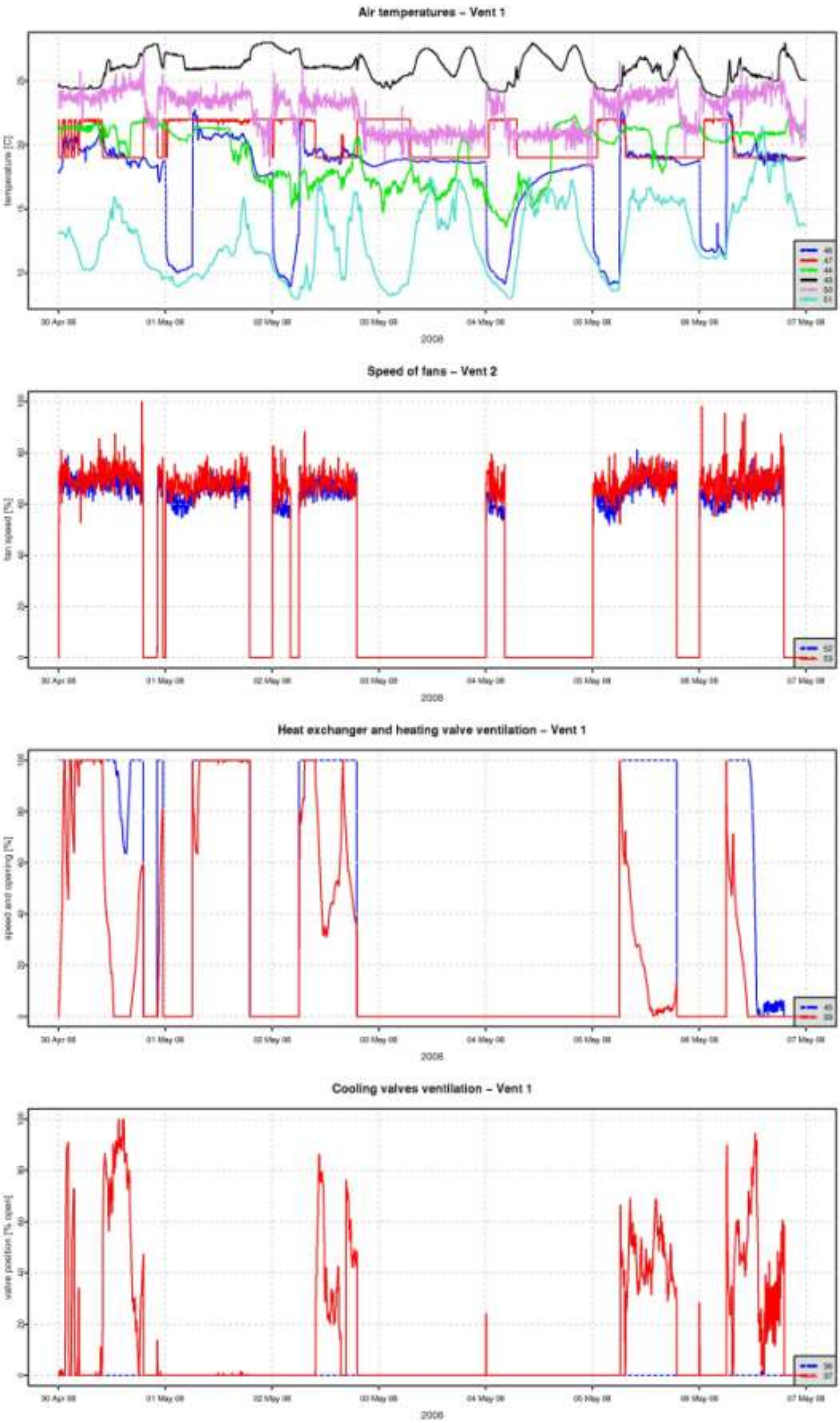


Figure 5.10. Values for Vent 1 – summer period.

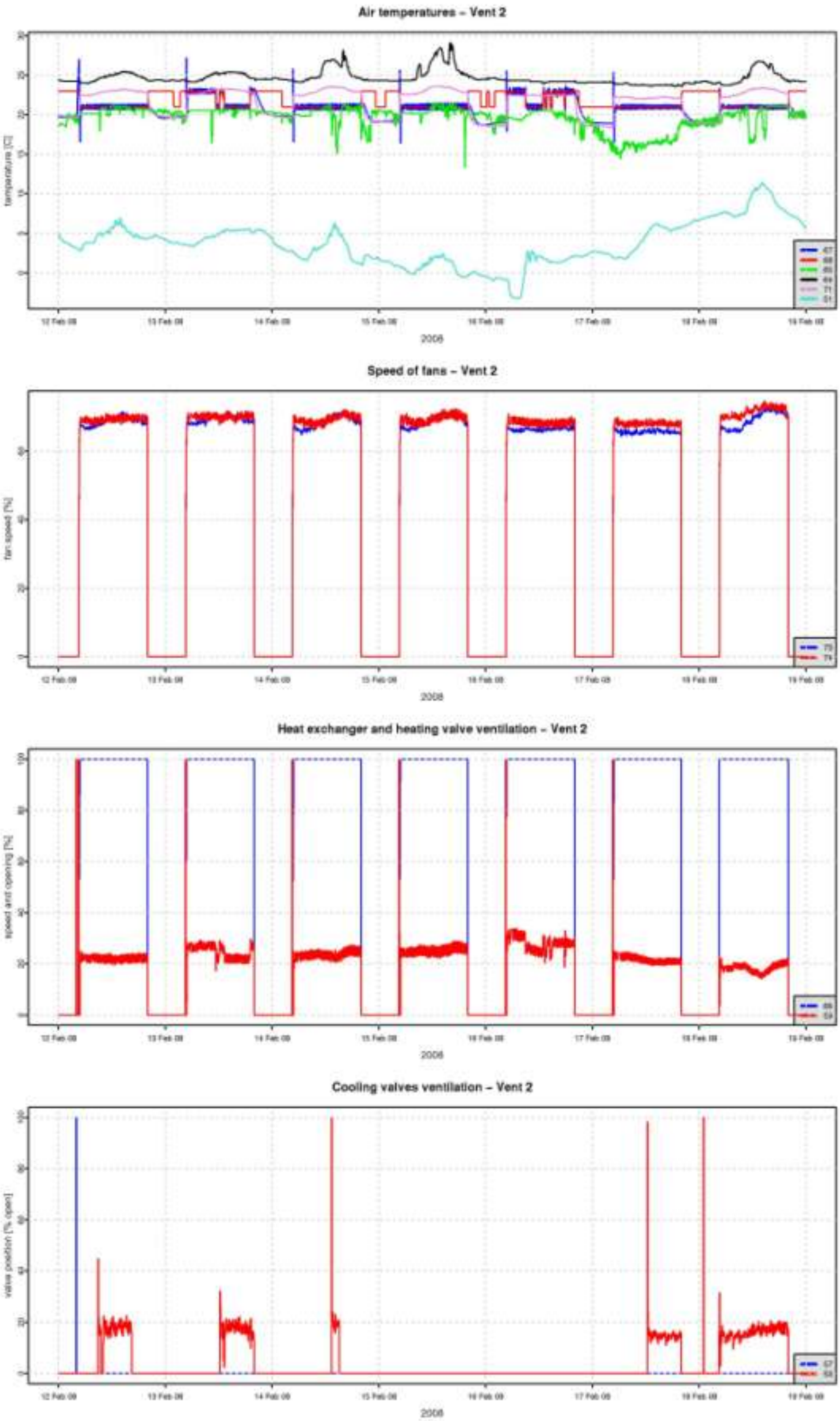


Figure 5.11. Values for Vent 2 – winter period.

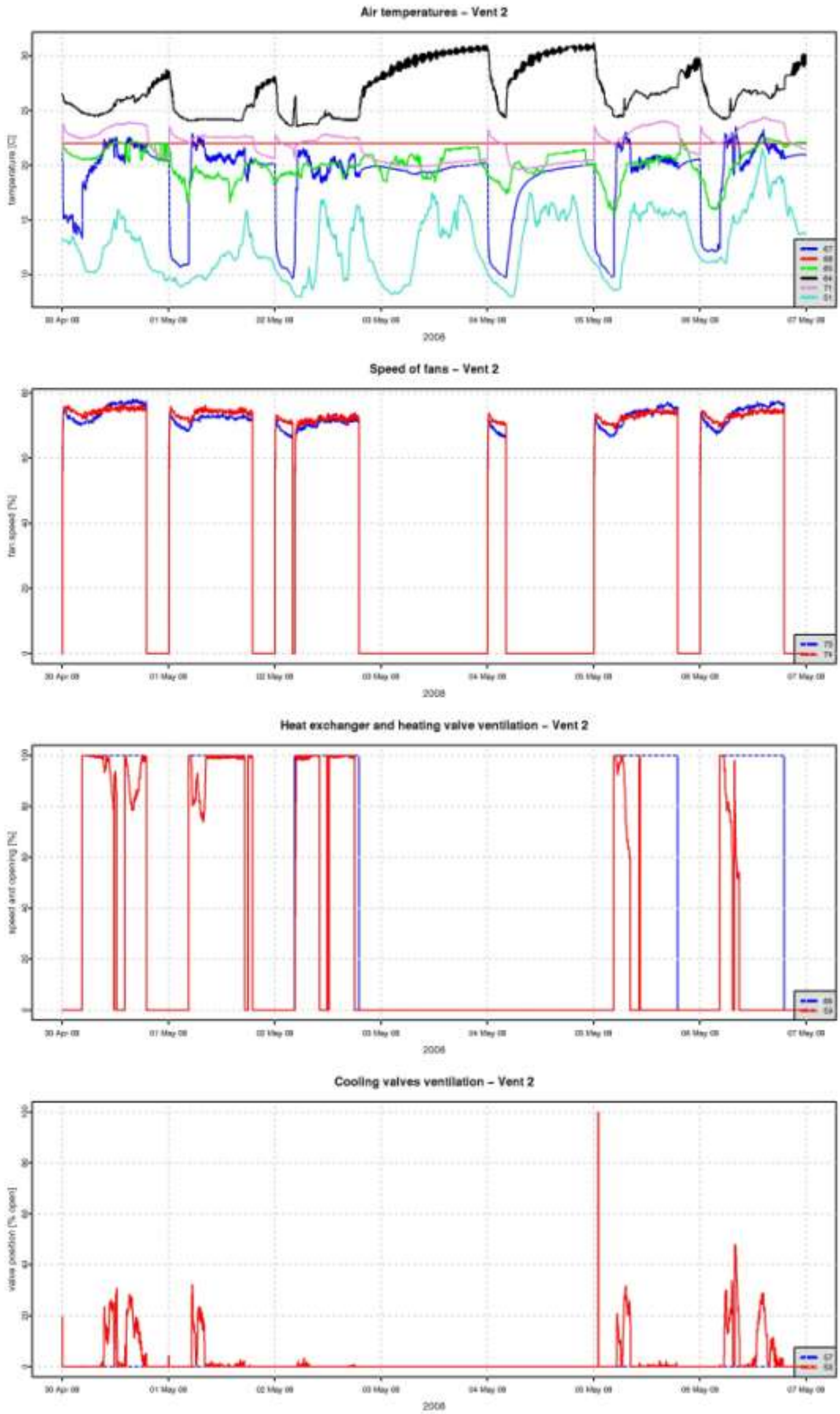


Figure 5.12. Values for Vent 2 – summer period.

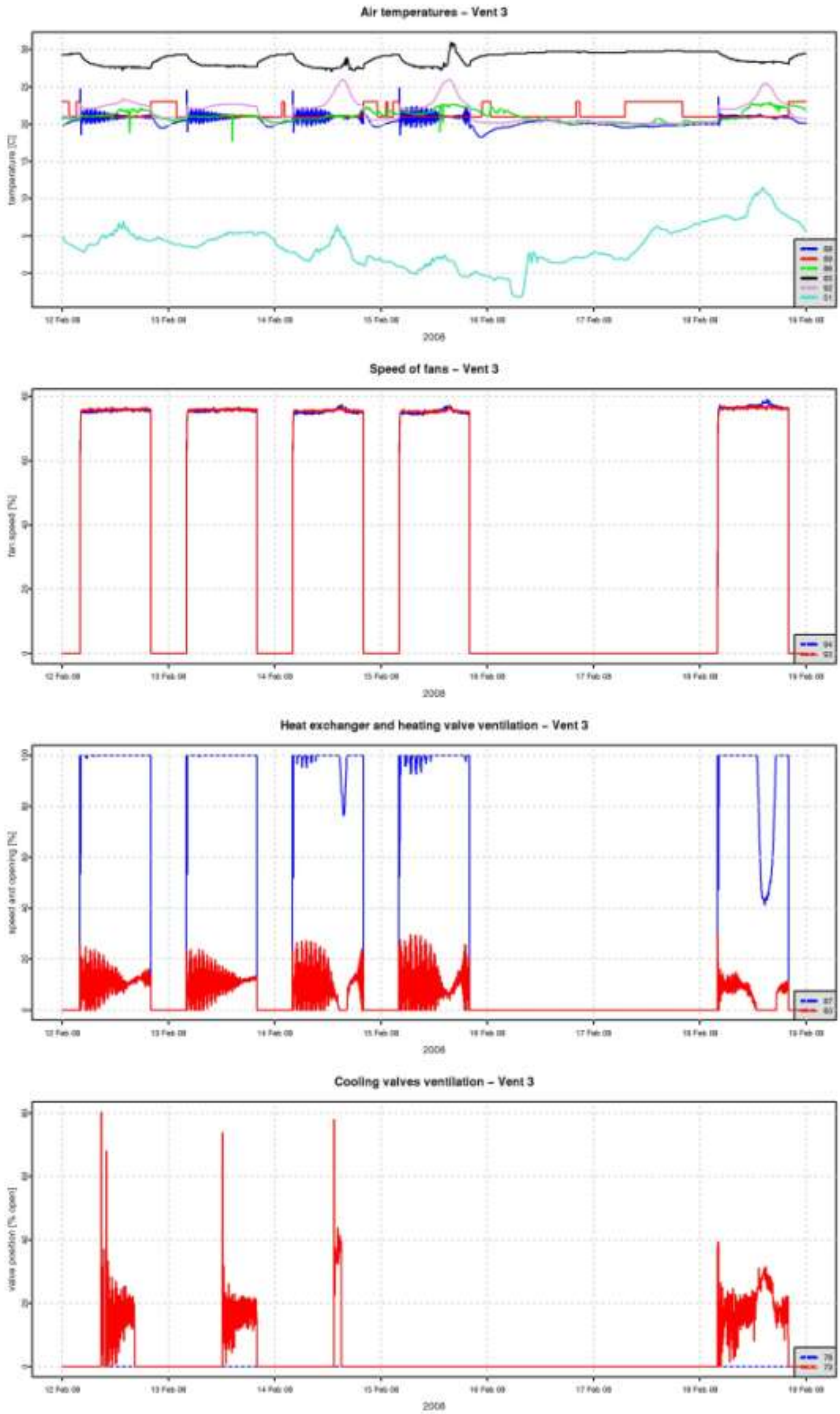


Figure 5.13. Values for Vent 3 – winter period.

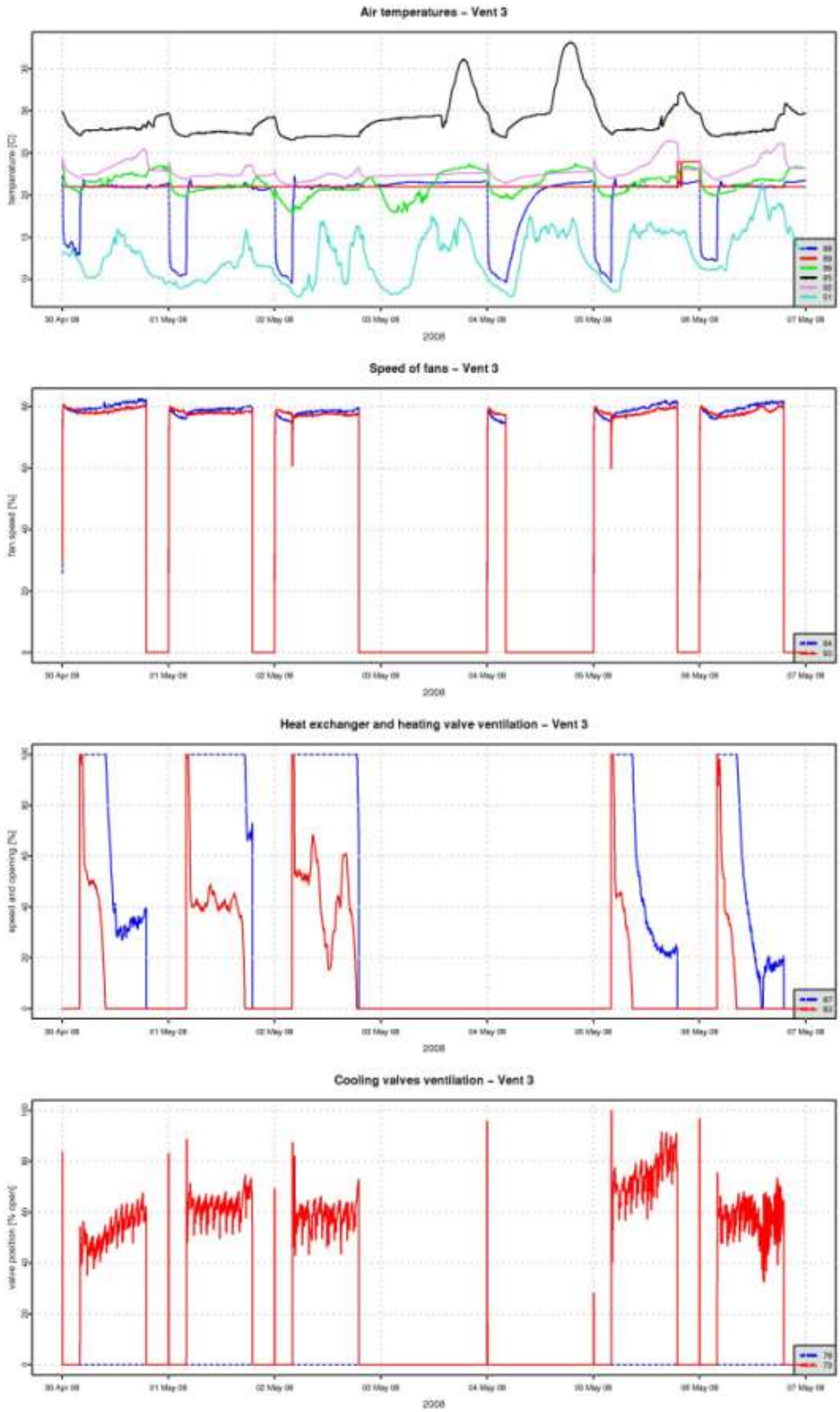


Figure 5.14. Values for Vent 2 – summer period.

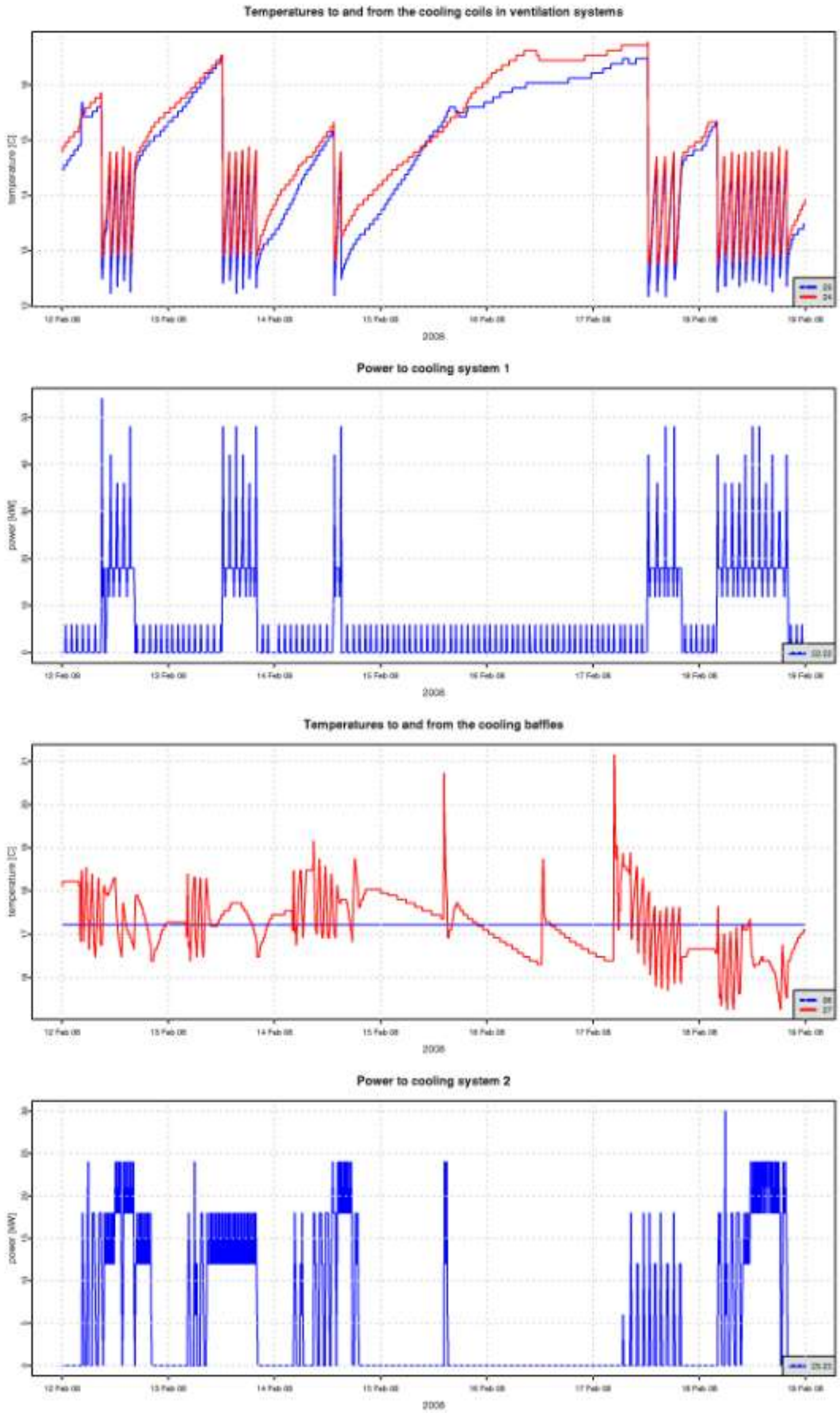


Figure 5.15. Temperatures and power for the cooling systems – winter period.

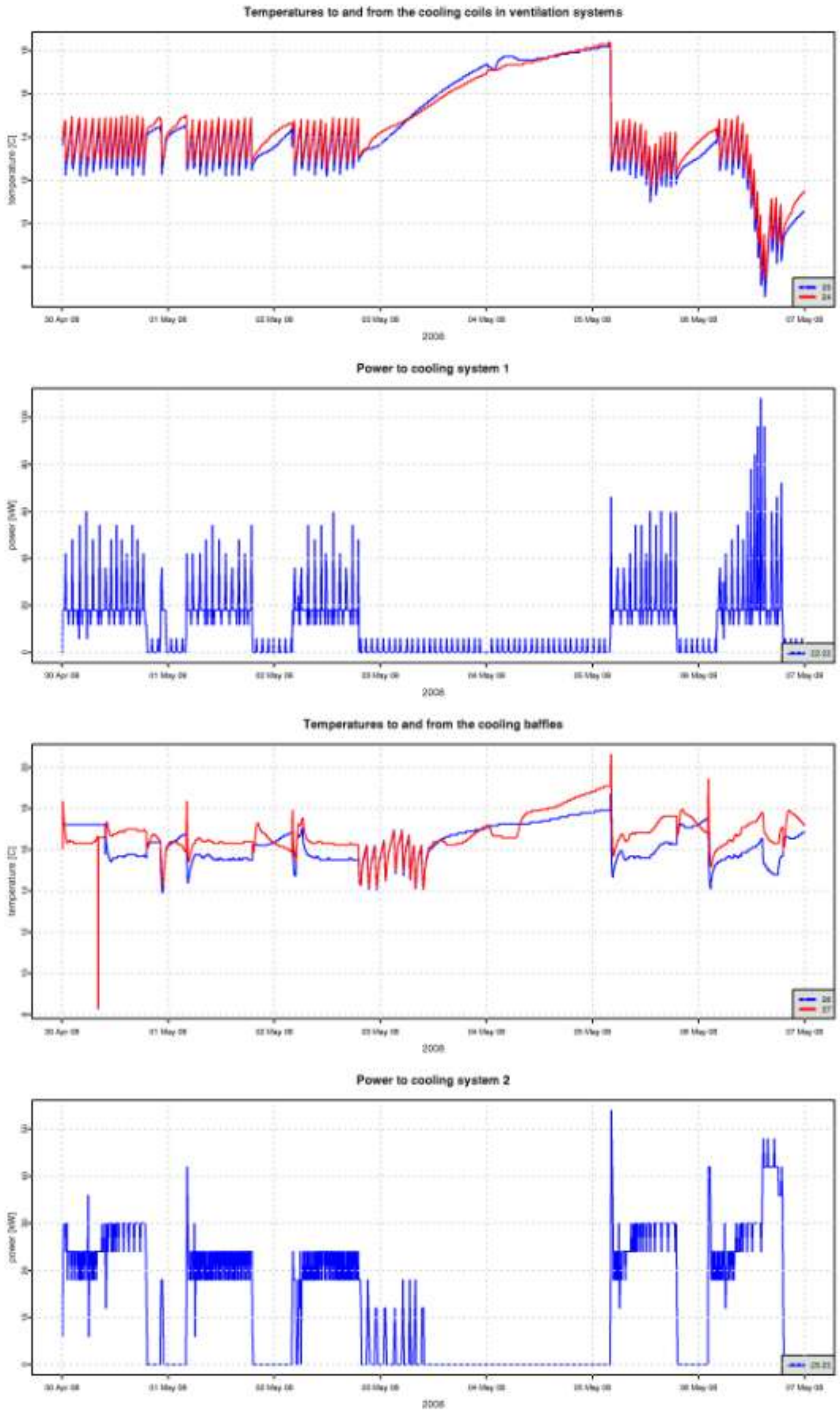


Figure 5.16. Temperatures and power for the cooling systems – summer period.

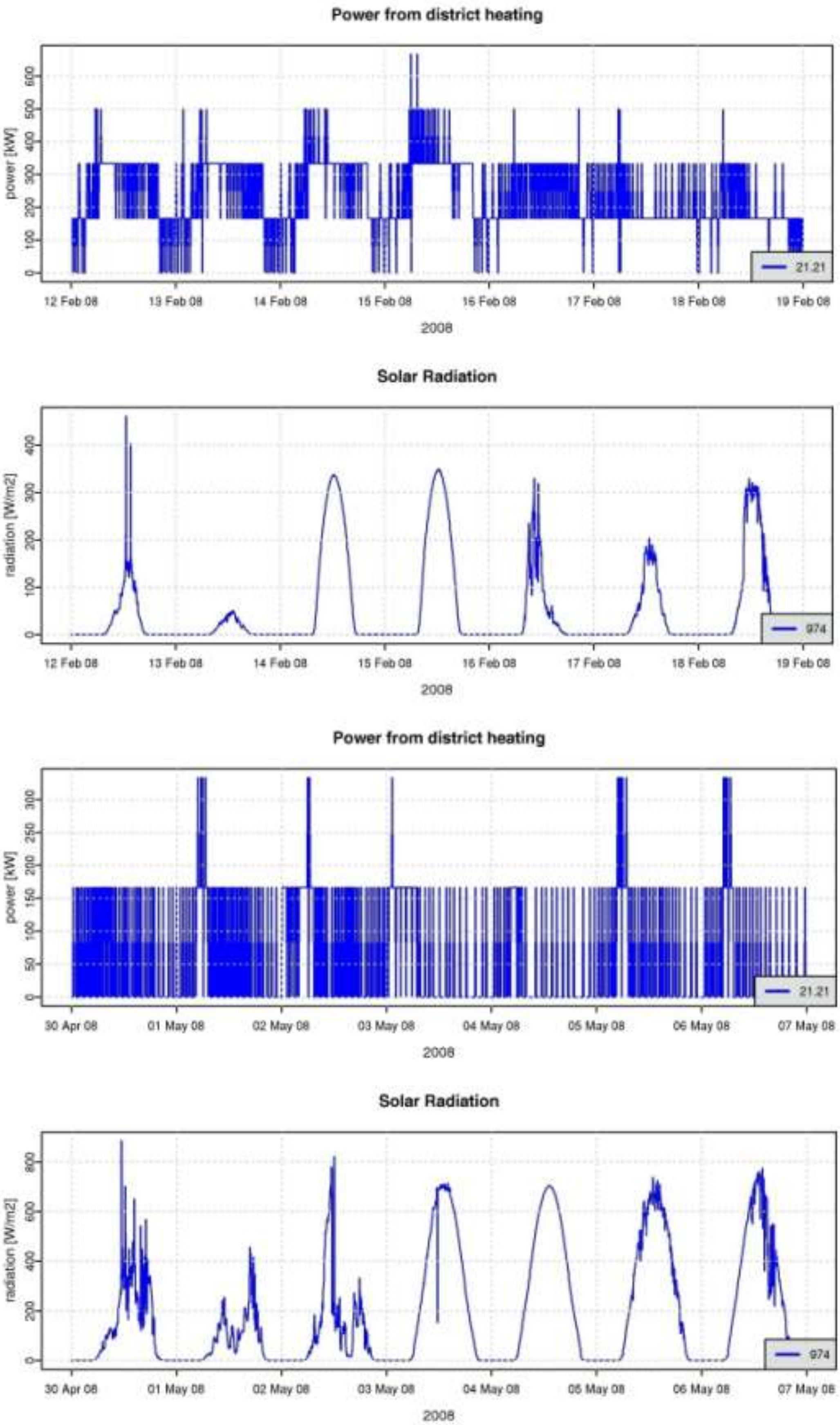


Figure 5.17. Power from district heating and global radiation – summer period.
Two top graphs: winter period – tvo bottom graphs: summer period.

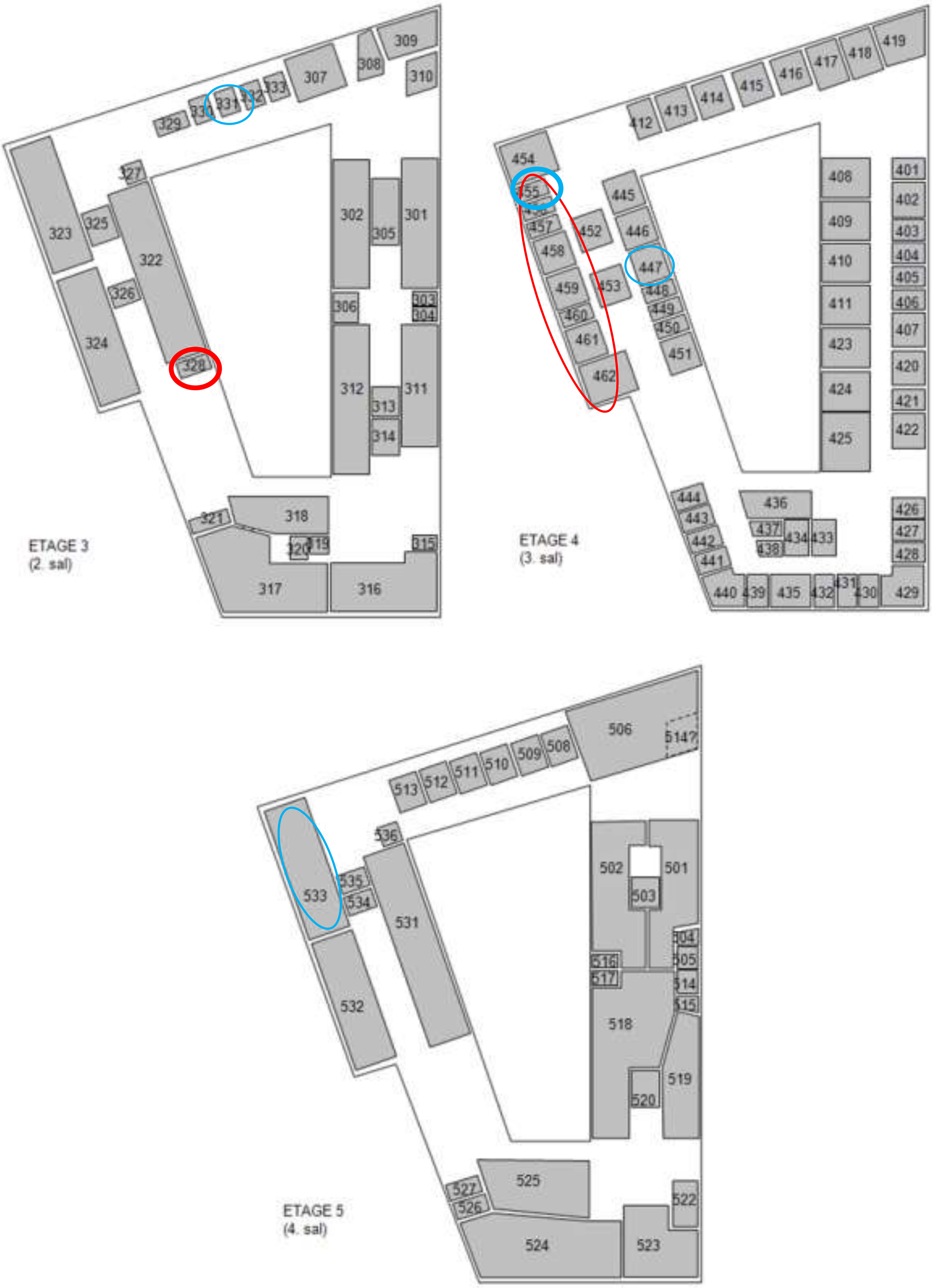


Figure 5.18. The location of the rooms causing the min and max temperature for ventilation system 3 – February 2008. Red circles are max temperature and blue circles are min temperature. The room with the circle with the fattest line is the dominant room.

In figures 5.9, 11 and 13 it is difficult to determine when the ventilation systems starts in the morning and stops in the evening. Figure 5.19 shows the % speed of the fresh air fan in all three systems. Originally it was the intention that the ventilation systems should start at 6 am and stop at 7 pm. From figure 5.19 it is seen that all ventilation systems stops at 8 pm but they do not start at the same time:

- Vent1 starts at 6:00
- Vent2 starts at 4:30
- Vent3 starts at 4:00

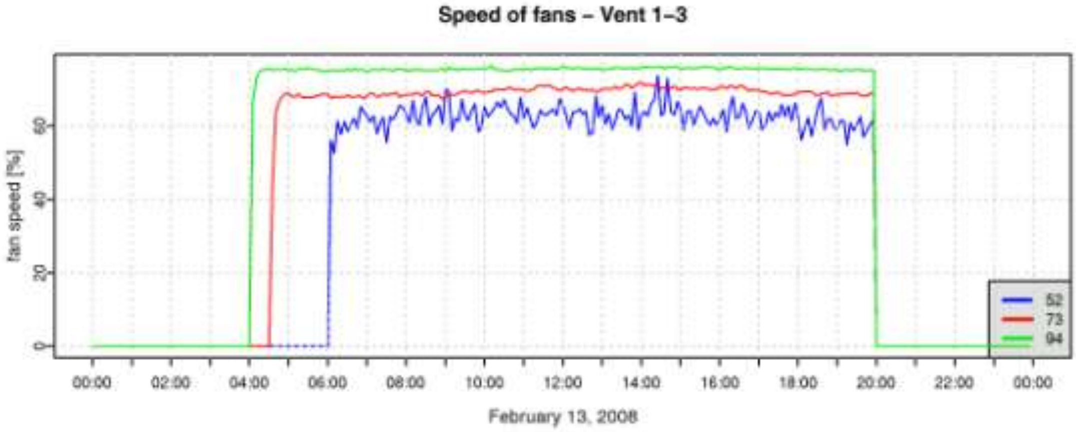


Figure 5.19. Start and stop of the three ventilation systems.
blue curve: Vent1
red curve: Vent2
green curve: Vent3

Much electricity and heat may be saved if the start and stop of the ventilation systems were changed back to the original start and stop hours of the day. Each ventilation system uses 22 kW at full speed but figures 5.9-14 shows that the fans did run at approx. 75% speed which leads to an reduction in the power by around 50% - ie to a power demand of each of the three ventilation systems of 11 kW. So if the operation of the ventilation systems is reduced with one hour per working day, the annual savings will be in the order of 3 MWh/year per ventilation system in saved electricity.

5.4.2. Ventilation system 3 – May 2008 – figure 5.14

May 3-4 is a weekend.

The second graph in figure 5.14 shows that the air flow rates of the ventilation system also here are very constant - now around 80% of the dimensioning flow rates. The flow rates are again a little less constant for ventilation system 2 – figure 5.12. And they are still very fluctuating in ventilation system 1 – figure 5.10. The latter should as earlier mentioned be investigated further.

The third graph of figure 5.14 the blue line shows that the rotating heat exchanger always starts at full speed – on May 1-2 the full speed remains most/all of the day while the speed on the other three working days starts to decrease just before noon but keep on running at 20-40 % during the late afternoon.

The opening of the heating valve is not fluctuating here – red line in the third graph of 5.14. It starts at 100 % but drops quickly to 50 % - on May 1-2 the valve remains 20-60 % open, while it closes just before noon at the same time when the speed of the rotating heat exchanger starts to decrease. The latter is correct: there is no need for district heating if the rotating heat exchanger can cover more than the need.

But there is a problem with the use of the heat exchanger and district heating during this period: the cooling demand in the building is so high that night cooling is necessary. The night cooling is according to the BMS documentation set to start at midnight and last until 4 am. Night cooling is also allowed during the weekend. The later is only utilized on Sunday May 4. On this day it can be seen that the night cooling starts at midnight and last until 4:15-4:20 – the night cooling is seen as a drop in the fresh air temperature: blue curve in the top graph of figure 5.14. At 4 am the rotating heat exchanger starts, the heating valve opens and the fresh air temperature increases to about 21°C.

Figures A5.3-4 in Appendix 5 show the air temperatures of the rooms served by ventilation system 3. The max temperature is again mainly generated by room 328 (value 454 – light blue line in the third graph in figure A5.4), while the peaks on May 3-6 (due to large solar radiation) again are generated by room 458 (value 769 – light blue line) closely followed by the other rooms in the bottom graph in figure A5.3. The min temperature is partly/mainly generated by room 461 (value 784 - the yellow line in the bottom graph in A5.3) while several of the rooms in the two bottom graphs of A5.4 are the min temperature or close to the min temperature – see the rooms in figure 5.20.

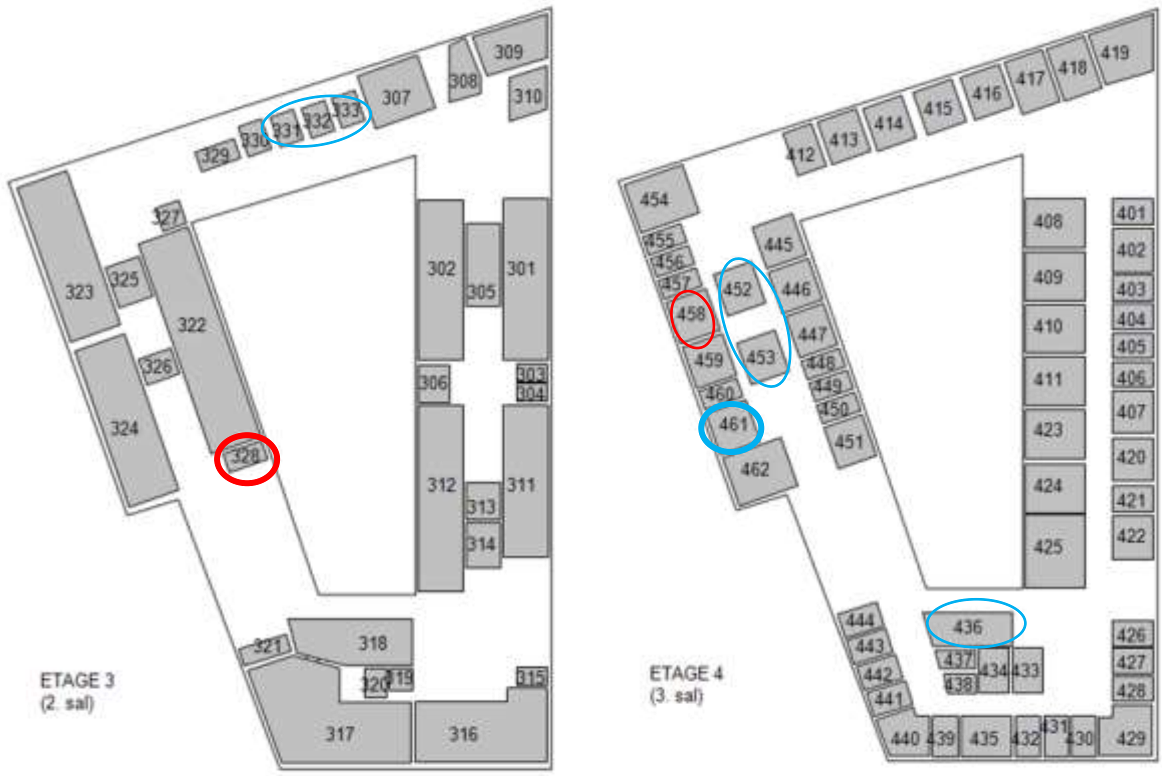
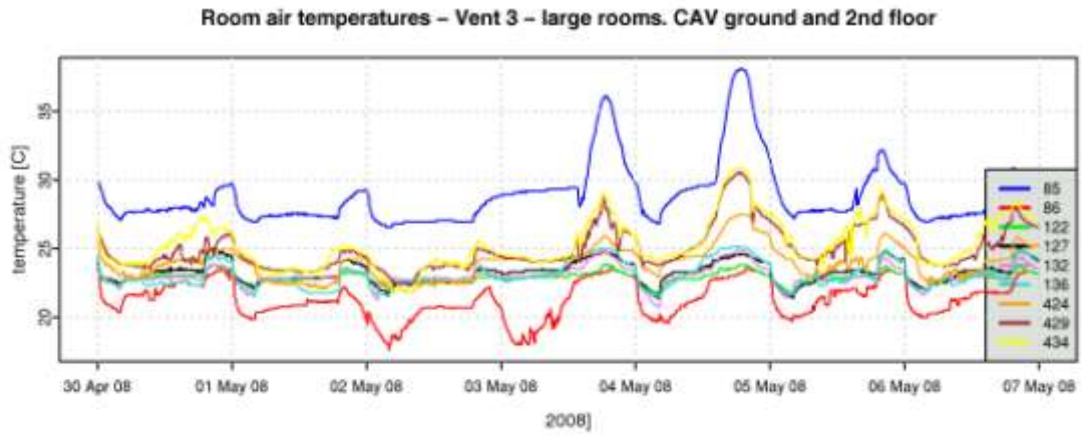


Figure 5.20. The location of the rooms causing the min and max temperature for ventilation system 3 – May 2008. Red circles are max temperature and blue circles are min temperature. The room with the circle with the fattest line is the dominant room.

Again it is seen that it is the small rooms that set the min and max boundaries and in this way have the main influence on the control of ventilation system 3. Small rooms more easily tend to both overheat and cool down. In figure 5.21 only the temperatures of the large rooms are shown: top graph: room 110, 111, 112, 113, 322, 323 and 324 (line 122, 127, 132, 136, 424, 429 and 434), bottom graph: room 220, 221, 222, 531, 532 and 533 (line 274, 279, 284, 936, 941 and 946). The air temperature of these rooms tend to stay more in the middle of the min/max range and they typically need cooling in the morning in order to bring the temperature down to the set point of the fresh air from the ventilation system. When comparing with the violet curve in the top graph of figure 5.14 (the exhaust temperature) it is seen that this temperature quite well represent the lower temperatures in the large rooms. Further the exhaust temperature is always above the set point of the fresh air temperature from the ventilation system suggesting that there is a cooling need also in the morning.



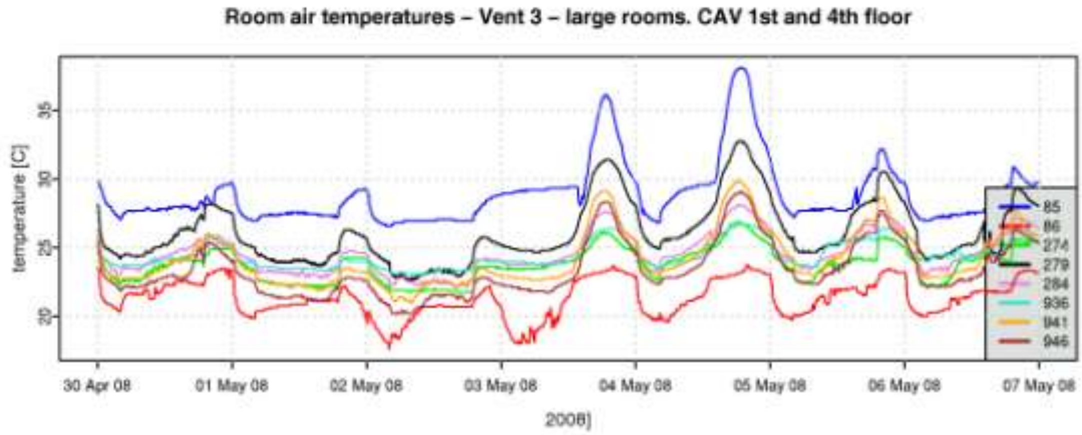


Figure 5.21. The temperature of the large rooms served by ventilation system 3. Blue line: max room temperature, red line: min room temperature.

This means that the heating in the morning with district heating is waste of energy – and further the heating of the fresh air (both by district heating and heat recovery) leads in this period to an extra cooling load – see figure 5.16. So instead of trying to reach the set point of the fresh air the system should continue free cooling until at least 6 am. Some rooms may then get too cold, but instead of heating the fresh air part of this heat may more efficiently be used to heat these few rooms. This will save heat and at the same time reduce the cooling load which has to be removed by the cooling baffles – and further lead to less overheating and thereby most probably to a better comfort.

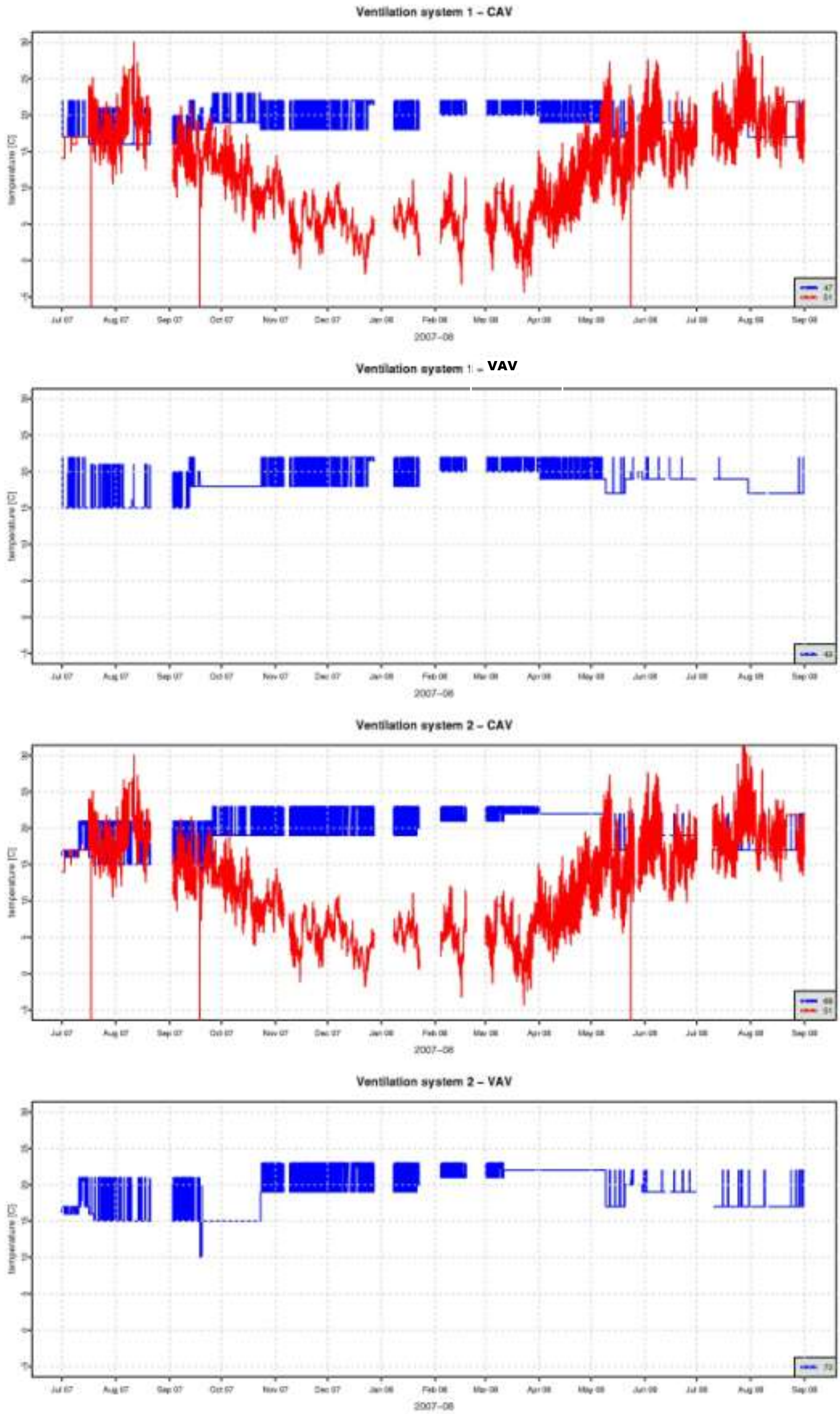


Figure 5.22. The set point for the fresh air temperature of ventilation system 1 and 2 for both CAV and VAV. Red line: ambient temperature.

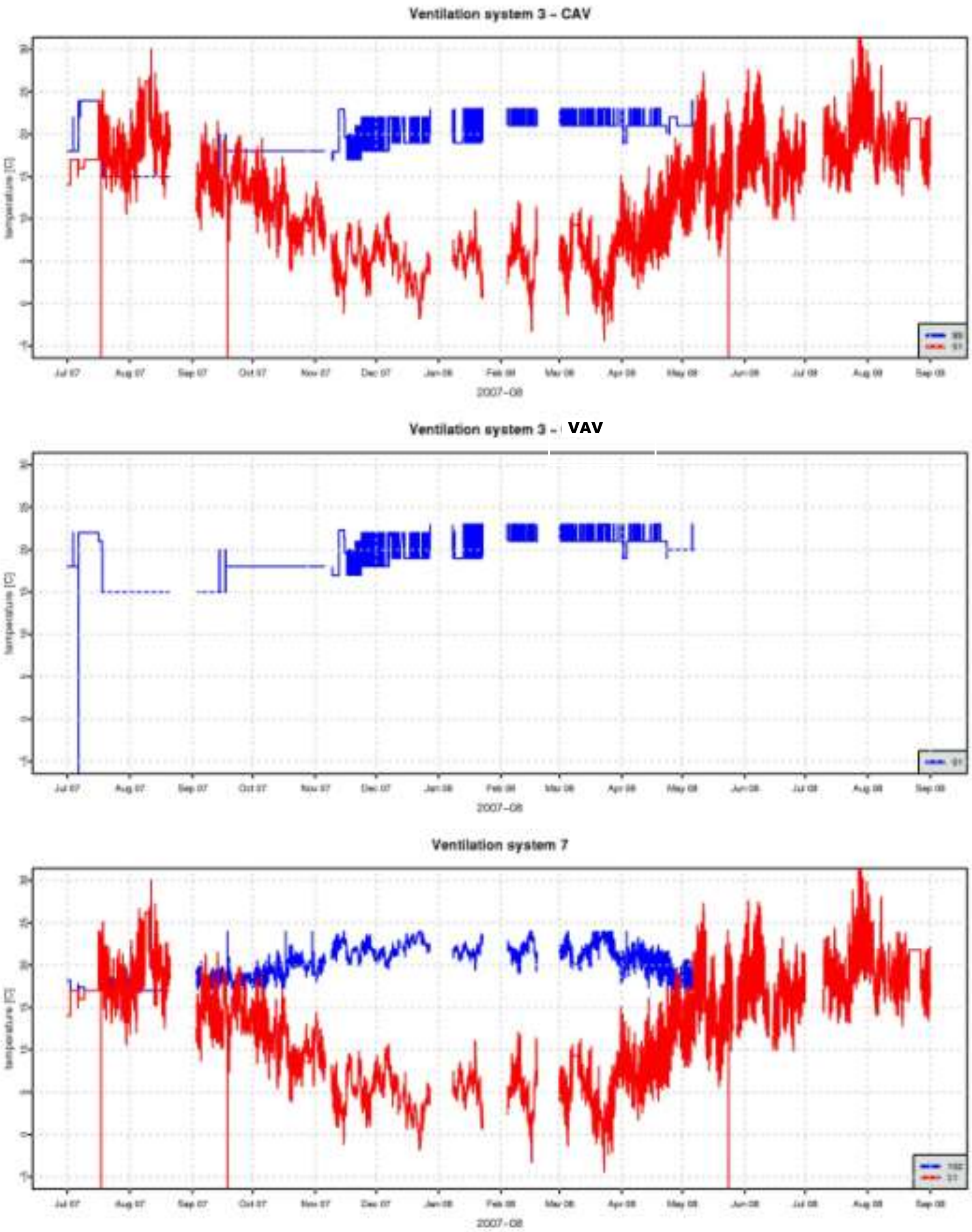


Figure 5.23. The set point for the fresh air temperature of ventilation system 4 and 7 for both CAV and VAV. Red line: ambient temperature.

The approach for ventilation system 1 is a bit better – see figure 5.19. Here the heating normally first starts at 6 am. But there is a bit confusion in the control of this system. On April 30 the heating starts already at 0 am. On May 2 the ventilation system stops between 4 and 6 am (which it is supposed to). On May 1, 5 and 6 the night cooling continues to work until 6 am which is good as the exhaust temperature often is high (purple curve in figure 5.10). The exhaust temperature is during this period very fluctuating – it is as already mentioned believed that this fluctuation is due to the very fluctuating air flow rates in the ventilation system.

5.4.3. General considerations

In figures 5.9-14 it is shown that the set point of the fresh air temperature from the three ventilation system changes between two values – see the red curve in the top graph of figures 5.9-14. Further it is seen that there is no obvious pattern in the way the set points change.

Figures 5.22-23 show the set points for the temperature of the fresh air – both CAV and VAV - to the rooms for ventilation systems 1, 2, 3 and 7. Figure 3.3 shows that three values have to be entered in the BMS with regard to the fresh air temperature TI1 – see also figure 5.24. Ventilation system 7 was installed later than ventilation system 1-3 and is different from the three other systems. The BMS screen for ventilation system 7 is shown in figure 5.25.

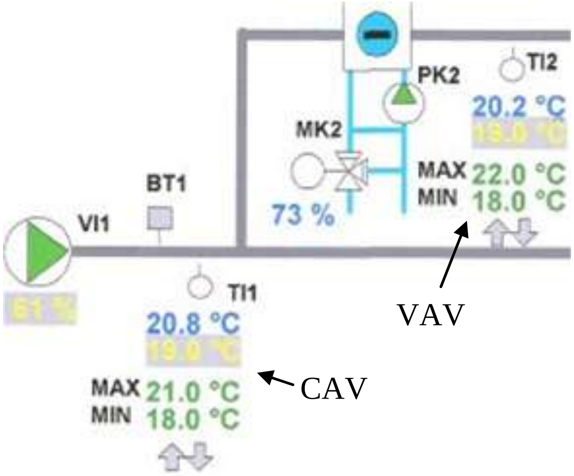


Figure 5.24. The set points for the fresh air temperature in ventilation system 1-3 – for both CAV and VAV.

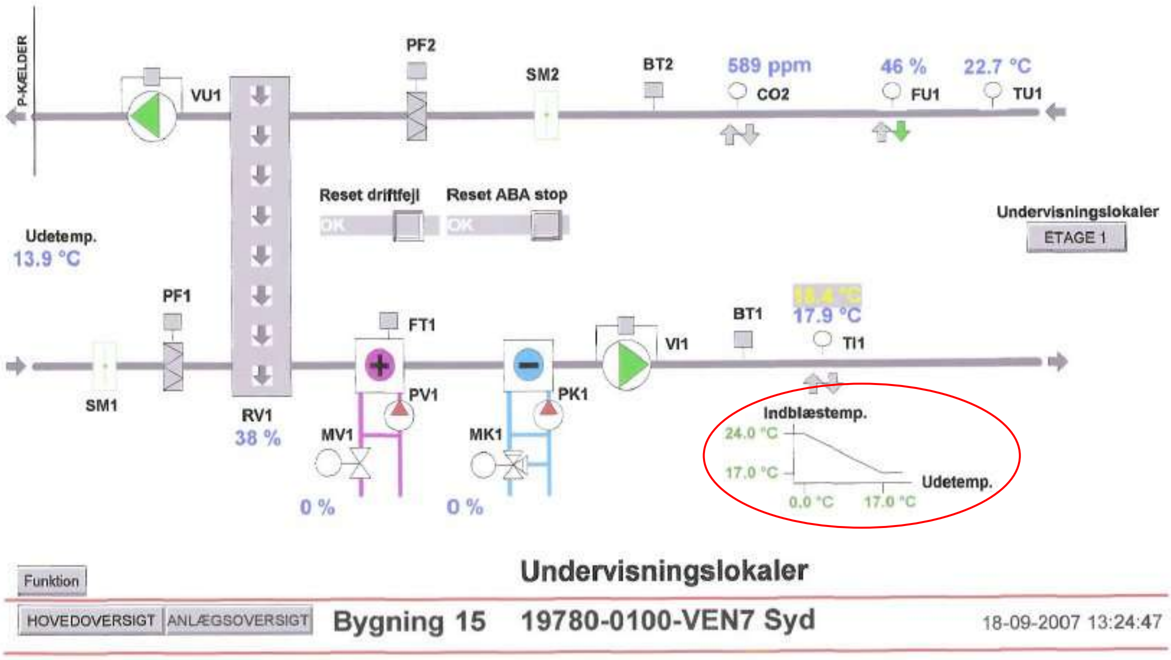


Figure 5.25. Screen dump of the BMS screen concerning ventilation system 7 (in Danish).

For ventilation system 1-3 three set points are entered manually: desired room temperature – yellow value in figure 5.24 and the max and min temperature of the fresh air. The min and max set point are according to the BMS documentation used in the following way:

- at low ambient temperatures the set point is the min set point. If all rooms need heat the set point is changed to the max set point
- at high ambient temperatures the set point is the max set point. If all rooms need heat the set point is changed to the min set point

This means as seen in figures 5.9-14 and 5.22-23 that the set point is either the min or the max set point – however mainly the min set point. Except for smaller periods the set points for CAV and VAV are identical. In figures 5.22-23 is also shown the ambient temperature. It can be seen that the set points have been changed dependent on the ambient temperature – most probably as a result of complaints. This illustrated that one should be careful: the optimal set points cannot be determined based on energy savings alone – it is necessary also to consider comfort.

The set points were originally: desired room temperature: 20°C while the min/max set points were 20/22°C. The cooling baffle system was renovated in the summer of 2009. The pipe works was flushed and valves were replaced. After this the set points of the fresh air temperature were altered to:

	desired	set points	
	room temp	min	max
Vent1:	17	17	22
Vent2:	17	17	24
Vent3:	18	16	22

Which is more or less in accordance with the summer set points in figures 5.22-23.

For system 7 there is an algorithm for determination of the set point: the red circle in figure 5.25. If the ambient temperature is below 0°C the set point of fresh air is 24°C. If the ambient temperature is above 17°C the set point is 17°C. Between these thresholds the set point is linearly dependent on the ambient temperature. Except to the more rapid fluctuations the level of the set point depending on the ambient temperature is quite similar to the manual changes of the set points in the three other ventilation systems. This suggests that it most probably would be a good idea to introduce an automatic change of set points in ventilation systems 1-3 so that this change should not be based on complaints or that the caretaker remember to introduce the changes dependent on the time of the year.

However there is a problem with the fresh air temperature from ventilation system 7 to the rooms as figure 5.28 shows. Figure 5.28 shows that the fresh air temperature is calculated correctly by the BMS (bottom graph in figure 5.28) but this temperature is not met by the ventilation system as the top graph of figure 5.28 shows. At the green line in figure 5.28 the fresh air temperature is identical to the ambient temperature suggesting that the heat recovery of the ventilation system is not in operation. The control and function of ventilation system 7 should be checked as energy may be saved if the system functions as intended.

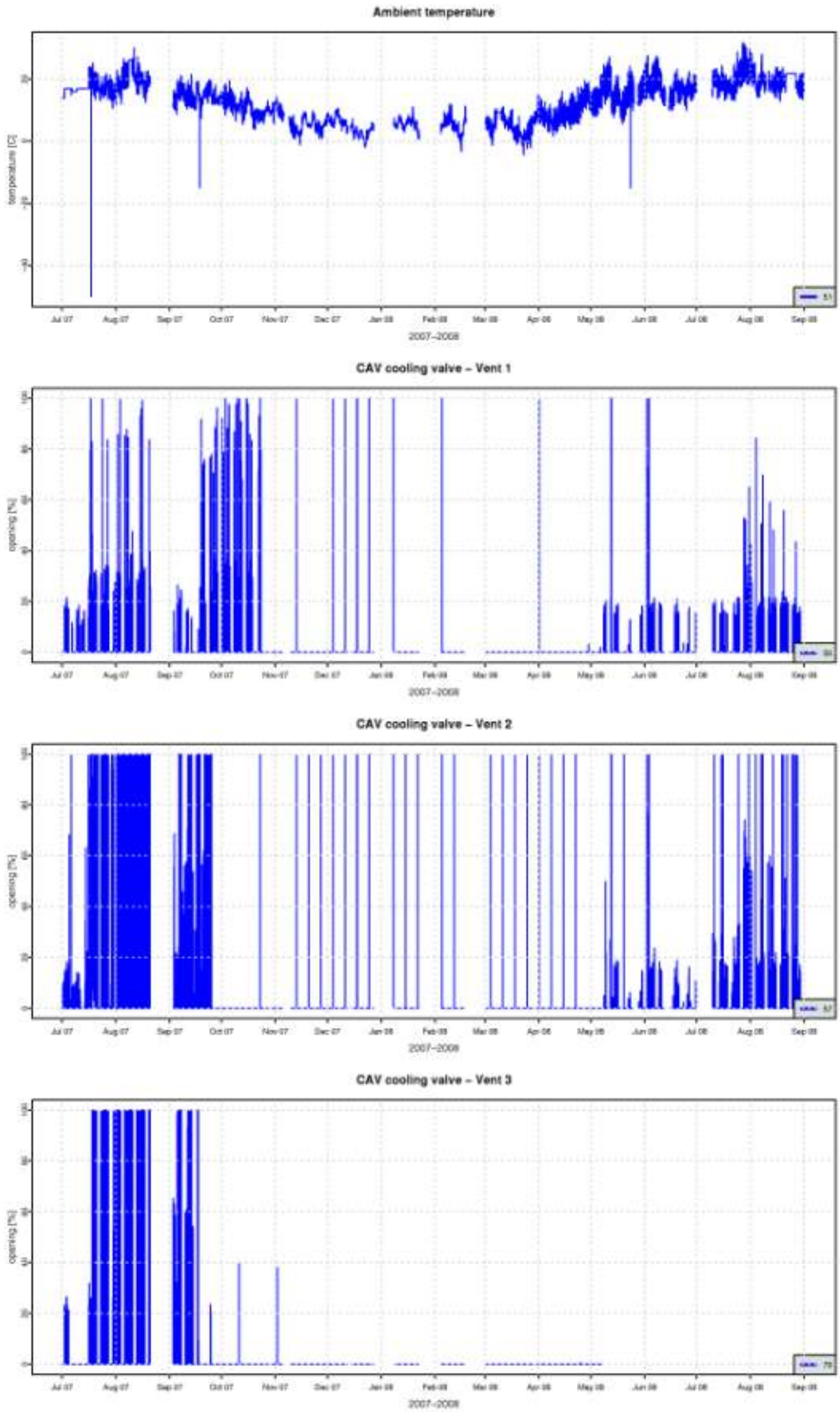


Figure 5.26. The position of the CAV cooling valve in ventilation system 1-3.

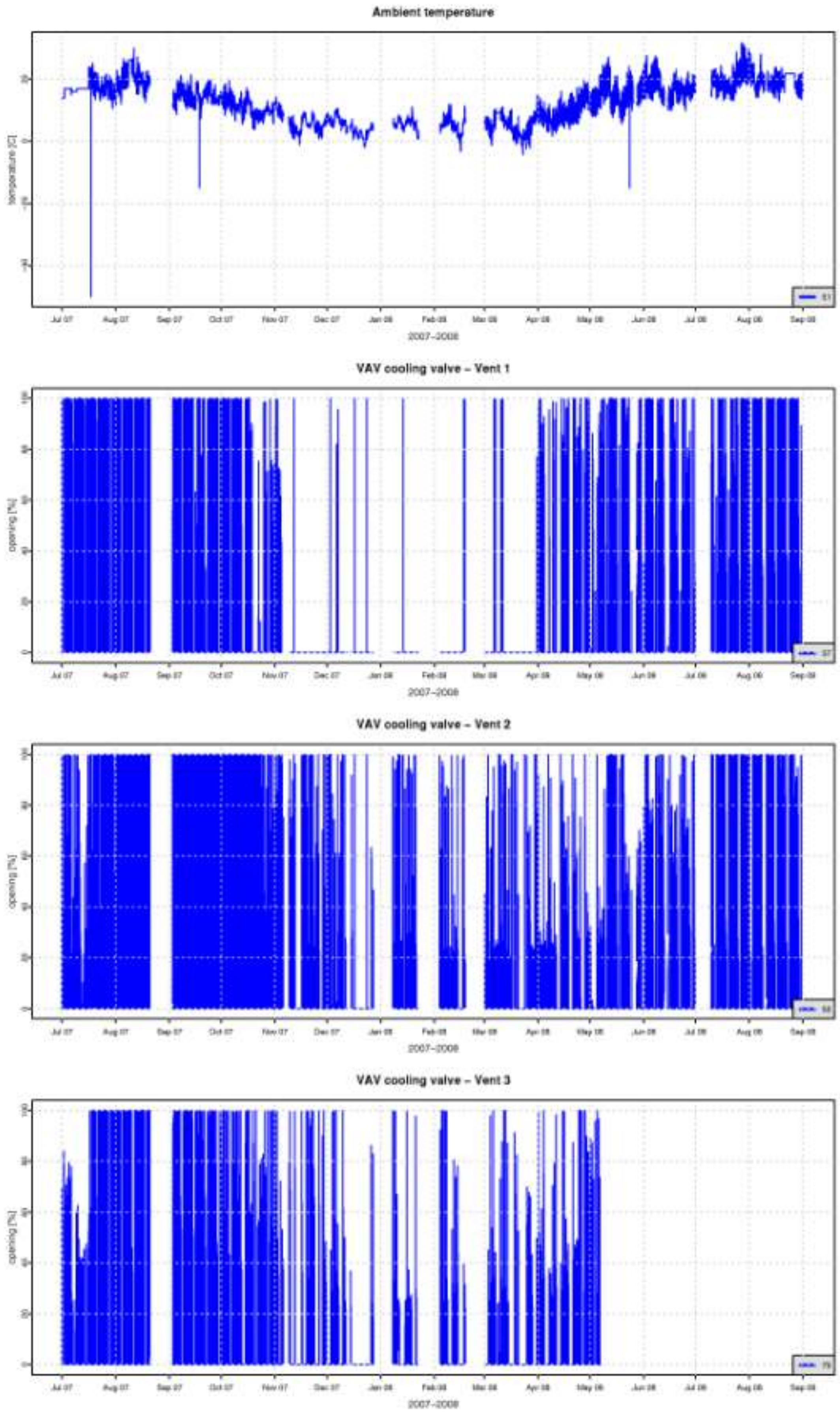
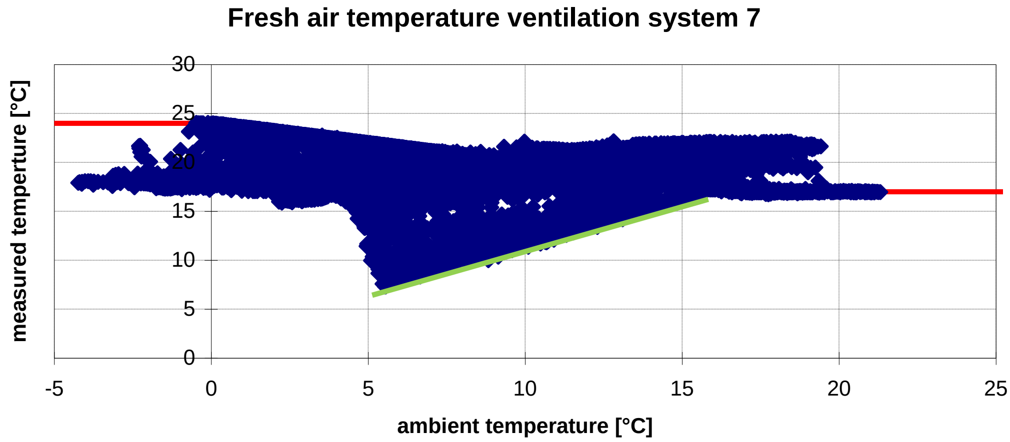


Figure 5.27. The position of the VAV cooling valve in ventilation system 1-3.

In section 5.4.1 it was stated that the cooling valve for the CAV part of the three ventilation systems was never open during the two shown periods. Figures 5.26 and 5.27 show the position of the CAV and VAV cooling valve in all three ventilation systems together with the ambient temperature.

In figures 5.26-27 it is seen that the CAV cooling valves may open during periods with high ambient temperatures. But it is also seen the VAV cooling valves is operated much more frequently and also during the winter period. The latter is natural because the VAV part of the ventilation systems mainly serves meeting rooms – often inside the building – with no cooling baffles. The operation of the cooling system will be dealt with in the following section.



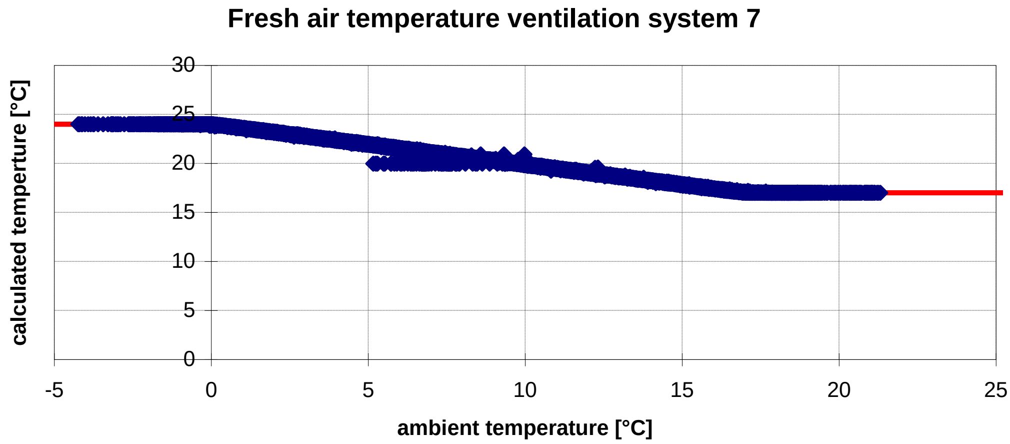


Figure 5.28. The measured and calculated fresh air temperature from ventilation system 7. The red curve is the set point temperature dependent on the ambient temperature.

Based on the above investigations the following may be recommended:

- the optimal time of the day for start and stop of the ventilation systems should be determined based on energy savings and comfort
- better utilization of night cooling should be implemented. Fresh air was often heated which lead to a following higher cooling demand
- the quality of the air in the building seems based on CO_2 and relative humidity measurements to be very good and there are problems with draft from the cooling baffles so a reduction of the flow rates of ventilation system 1-3 may be possible. This may solve the

draft problems and reduce the energy demand of the fans – a reduction of 30% in the energy demand may be possible. However, sufficient cooling power from the cooling baffles should still be available
- lower energy demand and better comfort may be obtained by introducing an automatic adjustment of the set point for the temperature of the fresh air
- fluctuation in air flow rates and opening of valves should be investigated and if possible be changed to a smoother regulation
- the control and operation of ventilation system 7 should be checked
- the function of the VAV part of ventilation system 1-3 could not be evaluated based on the measurements, however, a visit to the building showed one meeting room with too low a temperature. The VAV part of the ventilation systems should be checked

5.5. The cooling systems

The focus will in the following be on cooling system 1 (KØC1) as cooling system 2 (KØC2) is operating much more in accordance with the design conditions both with respect to the cooling unit and the layout of the installations. There is however a number of recommendations which will apply to both systems. These can be found at the end of this section.

5.5.1. Description of the load characteristics for KØC1

The cooling capacity of KØC1 is 755 kW with a compressor power input of 205 kW at summer conditions. This capacity is divided into the air volumes of ventilation systems 1, 2, 3, 4 and 7.

The total design air flow rates of these systems are 98,170 m^3/h and the refrigeration capacity corresponds to cooling the air from 28°C to 15°C. A temperature of 15°C after the cooling coil will result in a supply air of 16-17°C to the duct system. This is due to the heating of the air when passing the fan. The supply air set point is referring to the temperature sensor at the inlet to the duct system after the fan.

Due to the outdoor temperature distribution over the year the cooling of the fresh air will normally correspond to a load between 0 and 25 % for approximately 75 % of the operating hours over the year. Two factors reduce the load even further. Firstly: the set point for the supply air is most of the year approx. 1 K higher than the design condition. The set point for the supply air can be seen in figures 5.22 and 5.23 and for ambient temperatures above 15°C it varies from 15°C to 21°C with a mean value of 17°C to 18°C. Secondly: the actual cooled air flow rates are 22 % lower than the design air flow rates in table 2.1. The conclusion is for the measured period that the needed capacity for KØC1 will be less than 25% of max capacity during more than 85 % of the operating time.

From figure 5.29 it can be seen why this is crucial for the running condition of KØC1. The lower curve is relevant for this case, the figure shows that the capacity of the compressor can not be reduced below 25 % - ie meaning that KØC1 most of the time will be on/off regulated leading to a reduced efficiency.

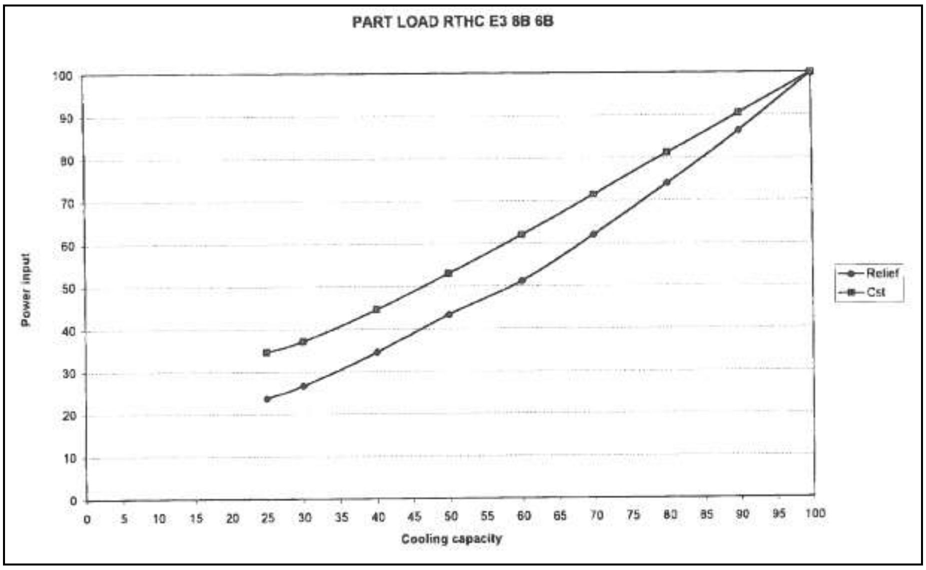


Figure 5.29. Part load cooling capacity and power input for KØC1 (Source: Chr. Berg A/S).

5.5.1.1. Analysis of part load condition for cooling system 1 during summer time

The 6th of May 2008 is chosen to represent summer conditions as this is the warmest day with a complete set of measured data. Graphs for the chilled water temperatures, the power consumption, the ambient temperature and the chilled water temperature differential for KØC1 are shown in figure 5.30 and will be analysed in the following.

The chilled water supply and return temperatures are seen in the upper graph. The characteristic saw tooth shape is a clear indication of start/stop operation of the compressor. The set point for the chilled water leaving KØC1 is controlled by the BMS system dependent on the ambient temperature. This is seen as a reduction in the temperature level starting before noon: around 10:15 (ambient temperature: 16°C) where the set point starts to decrease and around 14:30 (ambient temperature: approx.: 21.5°C – a small offset can be seen) the supply temperature has been lowered to 6°C. Later in the afternoon it stabilises at a level a few degrees higher.

The mechanism for the set point override is shown in the screen dump from the BMS system in figure 5.31. In the red circle the graph is showing the relation between the set point for the chilled water supply temperature on the y-axis and the ambient temperature on the x-axis. The temperatures on the x-axis can be adjusted by the operator and are not fixed. The current practice implies that these temperatures quite often are changed. This is why the drop in supply temperature in figure 5.30 occurs at ambient temperatures between 16 and 21°C and not as in figure 5.31 between 20 and 26°C.

The consumed power in the second graph of figure 5.30 shows two main characteristics. Firstly: the power spikes are mainly due to the operating of the compressor. Secondly: a baseline which is primarily representing the power absorbed by the pumps on both the warm side (heat rejection) and the cold side (chilled water).

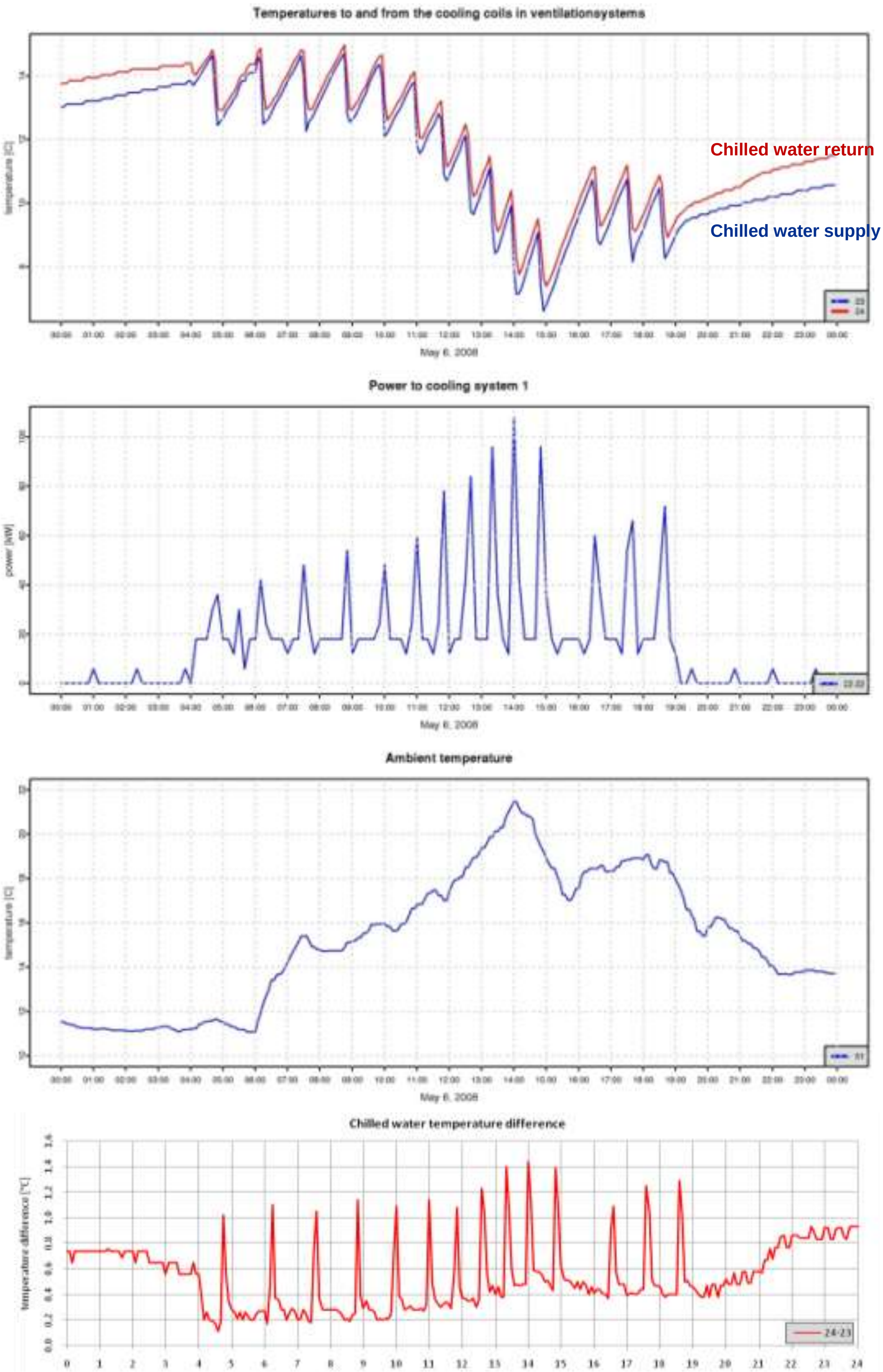


Figure 5.30. Temperatures of chilled water, absorbed power, ambient temperature and chilled water temperature difference for KØC1 May the 6th 2008.

The height of the power spikes appears to corresponds to the changes in the ambient temperature. It could be explained by the heat rejection at higher ambient temperatures: increased power consumption of the compressor and the dry cooler fans. The power consumption is in fact increasing around midday as can be seen from the shorter duration of the off periods (more frequent spikes) but a part of the load is constituted by the cooling down of the water in the system as the set point is lowered. During the night there are as seen small spikes with intervals of 1 hour 10 minutes to 1 hour 20 minutes (mean value 75 minutes). The power consumption is believed to be constant but the spikes are because the standby load does not reach the threshold level for the energy meter used. The power graph is a time derivative of the accumulated energy data. The minimum resolution of the energy meter is 1 kWh and the readings are sampled every 10 minutes. A load of 6 kW would be represented by a straight line as it would equal 1 kWh every 10 minutes. Smaller loads will be represented as spikes. In this case the night time load is 800 W. It should be investigated if this standby consumption can be reduced or eliminated.

From the graph at the bottom of figure 5.20 the chilled water temperature difference can be seen as spikes generated by the compressor corresponding to the power spikes. The height and duration of the spikes are almost uniform and do not reflect neither the ambient temperature nor the power consumption. As the chilled water flow is almost constant the temperature difference is proportional to the cooling capacity. This means that each starting of the compressor generates almost the same cooling capacity (modified by the possible minor variations in the water flow rate). The increase in the cooling load over the day is reflected in the frequency of the spikes.

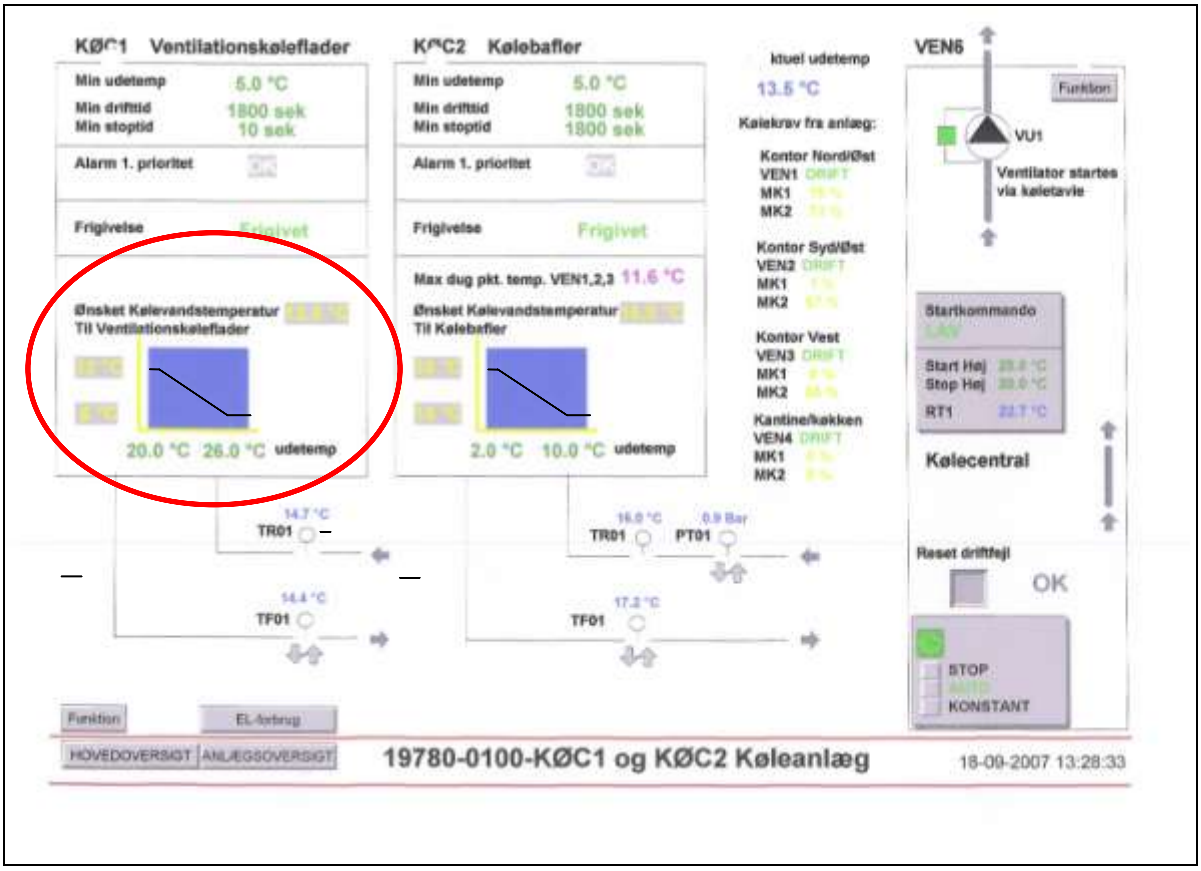


Figure 5.31. Screen dump from the BMS system with examples of set points for KØC1 and KØC2.

There is no information on the warm (heat rejection) side of the cooling system. It is, however, assumed that it is changing with the ambient temperature. In the following the three power spikes in the interval 7:00 to 10:30 (in the second graph of figure 5.31) and the three power spikes in the interval 13:00 to 15:15 are compared with the temperature change on the warm side (ambient temperature) between these two periods of approx. 6 K and the likewise change of 5 K on the cold side. The latter gives a total change in the difference between the cold and warm side of 11 K. As a rule of thumb it is normally assumed that for each degree the temperature span is increased between the cold side (leaving chilled water) and the warm side (in this case the ambient) the power consumption will increase by 3 % for a constant cooling load. This should then correspond to a change of 33 % of the mean heights of the power spikes from the interval 7:00-10:30 (mean spike height approx. 27 kW) to the interval 13:00-15:15 (mean spike height approx. 84 kW). But the height of the power spikes more than triple which is neither explained by the increase in fan power (maximum 25 kW) nor in cooling capacity.

It might be explained by an increase of the temperature difference between the condensing temperature and the ambient temperature over the day as the temperature build up on the warm side of the system. But this can only account for a small part of the change in the consumed power. There might however be an additional explanation: If the control system of the chiller unit interprets the off-setting of the set point as an increase in the load and correspondingly increase the capacity of the compressor, this will easily explain the size of the power peaks. If this is the case why is it then not reflected in the chilled water temperature difference? The reason is the on-off mode of the operation. The internal control system will start the compressor at a fixed difference above set point and stop it again at the set point.

The amount of energy supplied to the system is therefore primarily determined by the bulk of water cooled due to the very fast pull down time. Under more favourable circumstances it would be expected that the pull down rate would be reflected in the rate of change in the chilled water temperature and this would then correspond to the power spikes. Unfortunately the sampling times for the temperature and the energy measurement are 5 and 10 minutes respectively and this is not fast enough to give an exact measurement of the dynamic system in question. Furthermore the power is a calculated value (time derivative) of the energy meter with a minimum resolution of 1 kWh. This in itself gives rise to power spikes not accurately in accordance with the real instantaneous power consumption.

To conclude: the increased power consumption can be attributed to heat rejection at higher ambient temperature, increased fan power and the lower chilled water supply temperature.

When comparing the curves for ambient temperature and power consumption (second and third graph in figure 5.30) it seems that there is a direct correlation but actually there are more hidden variables. In figure 5.32 is shown the operation of the heat recovery wheels, the opening degree of the valve for respectively the heating coil and the CAV and VAV cooling coils. For the first part of the day there is a need for both heat recovery and heating of the air to the CAV part of the systems (see also the discussion in section 5.4.2). This is different for the VAV part of especially ventilation system 3 where there is a cooling demand during the entire day (bottom graph of figure 5.32). This is what initiates the operation of KØC1. Only for 45 minutes in the afternoon there is a very small cooling load for the CAV cooling coil of ventilation system 3 (third graph of figure 5.32). This means that in the first part of the day the majority of the air flow is heated and a part of the flow is then cooled by the VAV cooling coil and the rest of the air flow is distributed to the cooling baffles where a part of it again is cooled (by KØC2). This is as stated earlier not economical.

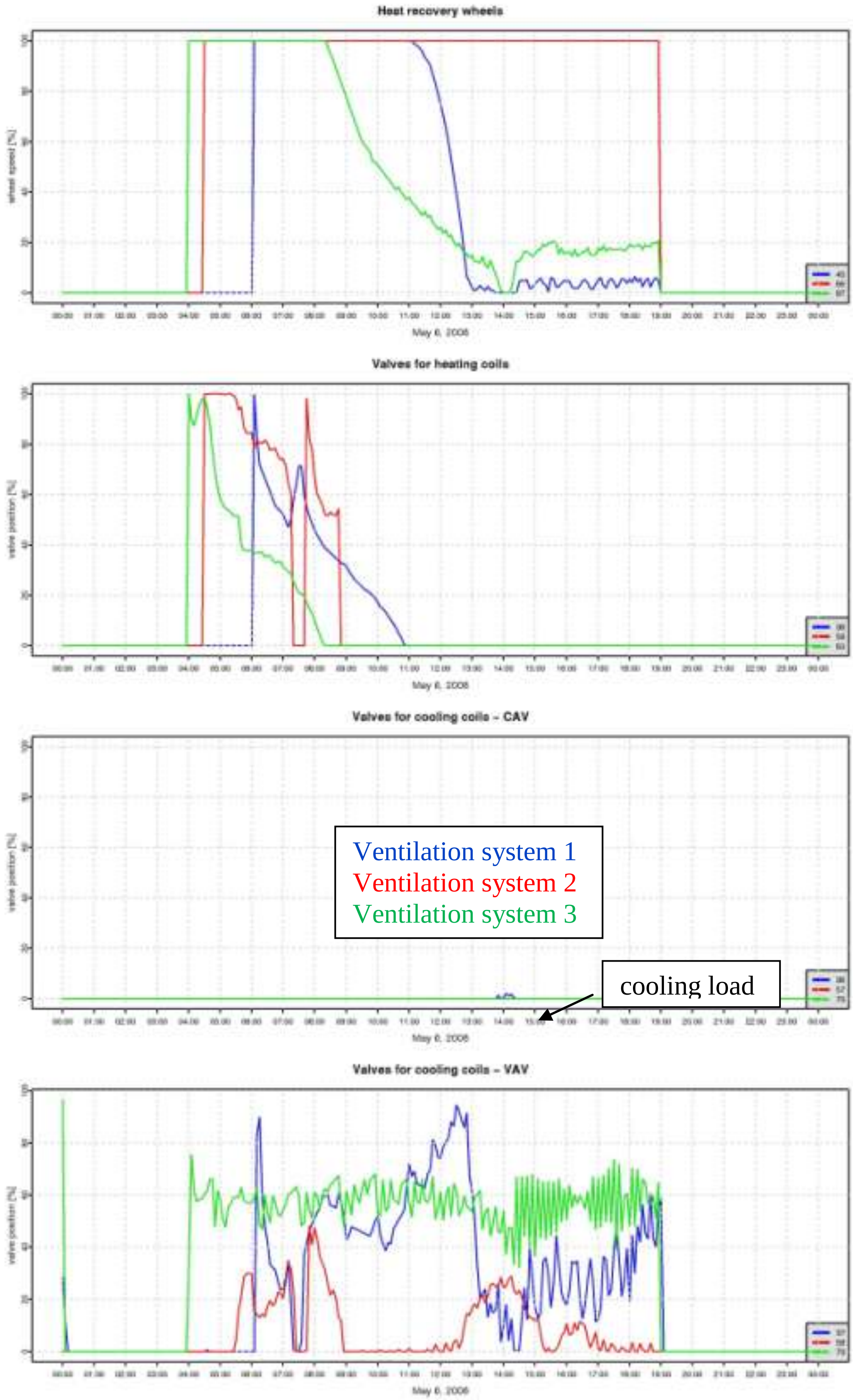


Figure 5.32. Opening degrees for heating and cooling valves for ventilation systems 1, 2 and 3. The wheel speed at the y-axis in the top graph is the speed of the rotating heat exchanger.

The blue line in the bottom graph of figure 5.32 shows the opening degree of the valve of the VAV cooling coil in ventilation system 1. A sudden drop in the opening degree is seen around 13:00. A similar but not so sudden drop can be seen on the same graph for system 3 (green line). When disregarding the possibility of changes in the VAV air flow the change in opening degree can be explained by the lowering of the chilled water set point to 6°C shown in figure 5.30 (top graph). This large drop in chilled water temperature is not needed as the opening degree of the cooling valve in ventilation system 1 drops from close to 100% down to 20%. Ventilation system 3 – with the highest demand – does neither need this large temperature drop, as the opening degree of the valve here never exceeds 75%. It might thus have been sufficient only to lower the set point of the chilled water by one or two degrees (and not 6 K as shown in figure 5.30) and thereby conserve energy.

5.5.2. Description of the load characteristics for KØC2

The cooling capacity of KØC2 is 255 kW with a compressor power input of 67 kW at summer conditions. KØC2 is designed for supplying chilled water to the cooling baffles with a supply temperature of 15°C and return temperature of 18°C. The part load performance is shown on figure 5.33. The lower curve is relevant in this case and when comparing it with figure 5.29 it can be seen that KØC2 is twice as efficient at 25% capacity as KØC1. In most cases the load will however be higher as it is dominated by the high internal heat load in the building and the contribution from solar radiation (see section 5.4 and the following section 5.6).

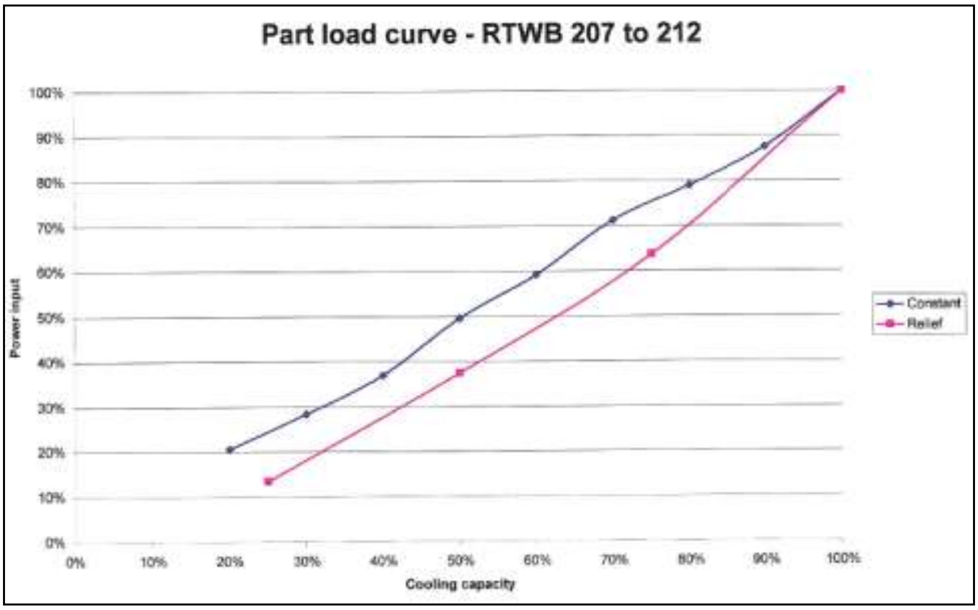


Figure 5.33. Part load cooling capacity and power input for KØC2 (Source: Chr. Berg A/S).

To illustrate the more favourable operating conditions of KØC2 the chilled water temperature and the power consumption for the 6th of May is shown on figure 5.34. It clearly displays the absence of abrupt starting and stopping during the day. It shows however also a set point change after 14:15 which is immediately followed by an increase in the power consumption. As in figure 5.30: the minimum resolution of the power graph for KØC2 is 6 kW hence the small spikes.

KØC2 may utilize free cooling. At ambient temperatures approx. 5°C below the chilled water supply temperature it is possible to cool the water directly with the glycol from the dry cooler on the roof via a plate heat exchanger. At winter conditions this should reduce the running time of the compressors significantly and hereby lower the energy consumption. Unfortunately the data set is incomplete for the winter period and it is thus not possible to analyse this further. It can however be seen from figure 5.15 showing the power consumption in February that if the free cooling was active a lower power consumption would be expected. Power spikes also indicate stopping and starting of KØC2 indicating a very low cooling load. The absence of stand by loads indicates that the power consumption of fans and pumps is measured on another energy meter.

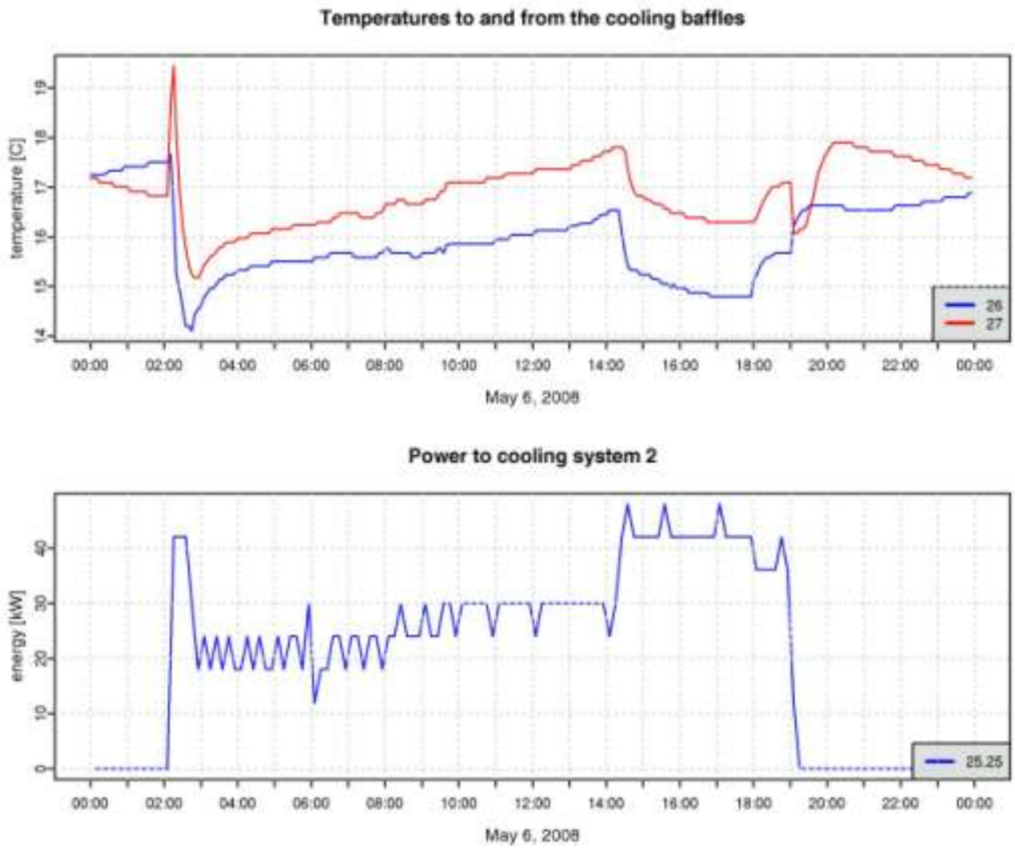


Figure 5.34. Supply and return temperatures and power consumption for KØC2 the 6th of May 2008.

5.5.3. Power consumption for the cooling systems over the year 2008 compared with the 6th of May.

The accumulated energy consumption for the 6th of May for KØC1 is app. 410 kWh. Of these are app. 240 kWh consumed by the pumps and the remaining 170 kWh are accounted for by the compressor (and possibly the dry cooler fans). In figure 5.35 is the daily energy consumption for KØC1 shown for the period mid October 2007 until beginning of May 2008. Even if it cannot be read from the graph how many operating hours per day are represented it is a conservative guess that the ratio between pumps and the compressor remains fairly constant in that period. This means that for the majority of the year the pumps account for more than 50 % of the energy consumed. This is primarily due to the pumps being designed to handle the full load situation which very rarely is the actual running condition. This is also indicated by the very minimal temperature difference on the chilled water for KØC1 – figure 5.30. The three pumps have each a power demand of 5 kW. An inspection of the three pumps showed that only one of the pumps was equipped with inverter and it was running at full power even under the part load condition present during the visit.

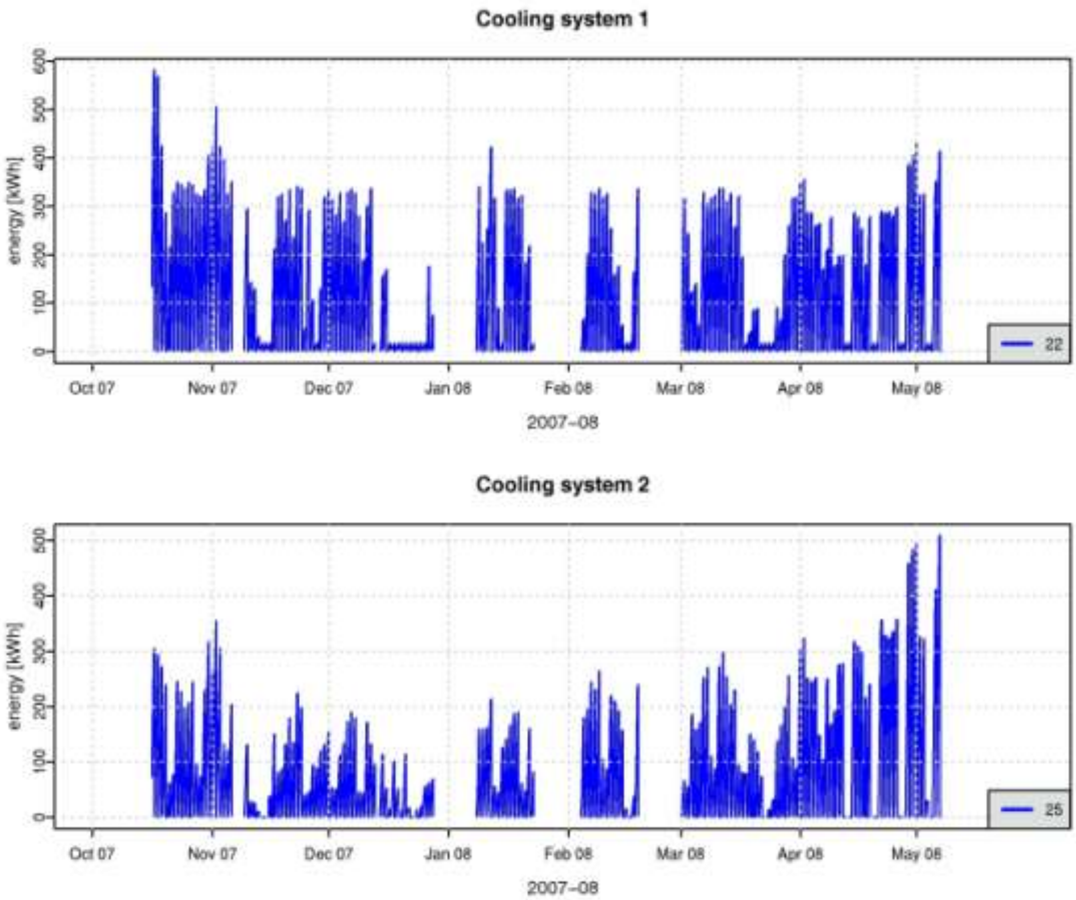


Figure 5.35. The daily energy consumption for KØC1and KØC2 for 2007-8.

Data from the months May, June, July and August are missing in figure 5.35. In order to get an idea of the energy consumption in this warmer part of the year please see Appendix 4 Electricity consumption and the graph “Power to installations” (which includes the power of KØC1 and KØC2).

It can be seen that the maximum power peaks are app. 300 kW compared to the app. 175 kW on the 6th of May of which KØC1 and KØC2 contributes 108 kW + 47 kW = 155 kW. The power peaks are assumed to be caused by the higher load of the cooling systems. On the other hand there is no full load condition represented as the KØC1 and KØC2 would use approx. 330 kW including pump and fan motors. Even if the energy consumption is expected to reach a substantial amount in the summer months due to the higher number of operating hours, the load on the cooling systems remains moderate. This is true especially for KØC1 which is partly explained by the set points in the period for the CAV cooling coils (figures 5.23 and 5.24).

Based on the above the following recommendations for improved operation of the cooling systems can be given:

- the controls in the BMS system should be modified in order to enable operation with the highest possible chilled water supply temperatures
  - for KØC1 by the use of control valve opening degree to initiate set point adjustments and delete the ambient related override function
  - for KØC2 by the use of the humidity probes to determine minimum chilled water supply temperatures equal to the dew point temperature to ensure high performance in the months with high humidity and maybe enable higher supply temperatures in the other months and thus maintain high free cooling performance in the cold months
- reduce the operating time for the cooling systems (and maybe ventilation systems). By disabling compressor operation in the cold months and evaluate the need for early morning operation of the ventilation systems which initiates simultaneous cooling and heating with no people in the building
- reduce pump and fan power
  - install an inverter on the main circulation pumps without inverters and establish convenient controls by the BMS system in cooperation with the chiller supplier
  - check and evaluate with the chiller supplier the controls of the fans for KØC1 in low load mode.
- reduce the standby consumption during the night for KØC1. Investigate if there is a standby consumption for KØC2.
- facilitate monitoring of the heat rejection temperatures thus enabling the evaluation of a new control strategy
- it could be investigated if it was possible to interconnect the chilled water loops of KØC1 and KØC2 and in this way enable the possibility to supply the cooling of KØC1 in the winter by free cooling. It would then be possible to have the set point for the VAV inlet air lower than the CAV inlet air with out initiating operation of KØC1

The above recommendations will when implemented and tuned in result in considerable energy savings – up to 50%. Figure 5.35 shows that there are not measurements for a whole year of the electricity demand of the cooling systems, however, in section 5.9.2 it is estimated that the electricity demand of the cooling systems constitutes about 50% of the annual electricity demand for installations. The energy label in figure 2.19 states an annual electricity consumption for installations of 733,865 kWh, which means that the annual electricity consumption of the cooling systems is in the order of 370 MWh. This leads to a potential of savings for the cooling systems of up to 185 MWh. But comfort issues may reduce the potential if eg. lower supply temperatures than assumed here are necessary in order to obtain sufficient cooling during warm periods.

5.6 Temperatures in the rooms

Curves showing time series of temperatures can be difficult and time consuming to read and evaluate – especially when there as in Tuborg Boulevard 12 are 170 rooms. Instead cumulated frequency curves (see below) may in many cases be a more useful tool due to the large amount of information gathered in a single curve which is easy to interpret. These curves make it also easy to compare the temperature conditions in different rooms.

In order to transform the observed room temperatures to a useful tool for analysing the thermal performance of a building the analysis below is performed. The intention is to use the historical data to investigate if these observations are a sign of a certain pattern which is acceptable or if adjustments in usage or operation of the building should be considered in order to save energy and/or improve the comfort level.

For all the rooms in the building the frequency curves of the room temperature were generated. The frequency curves show for a certain temperature the share of the total hours with temperatures below the certain temperature. An example is shown in figure 5.36. The values of the frequency curves are generated by the program R – see Appendix 7.

The frequency curves generated are:

- *Work hours* (shown with red curves)
- *Outside work hours* (i.e. most data is from night time and weekends) (shown with green curves) – in the text also referred to as “other hours”
- *All values* (all hours is shown with black curves)

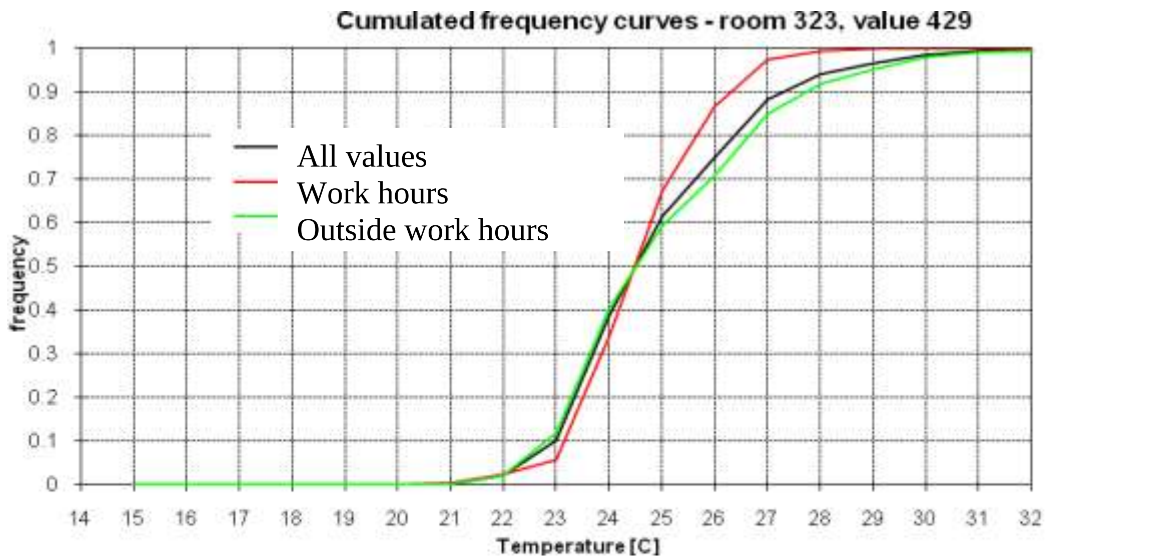


Figure 5.36. Example of frequency curves (room 323).

In the figure 5.36 it is possible to see the frequency (share) of the hours which exceed 26 ºC and 27 ºC. It is normally recommended (SBi, 2000) not to have more than 100 hours with temperatures higher than 26ºC during working hours within a year. This corresponds to 4 % of the work hours which is equal to a frequency of 0.96. On the red curve shown in figure 5.36 this number can be read to approx. 0.86 which means about 350 hours above 26ºC. So the room fails this recommendation. It is further recommended not to have more than 25 hours with temperatures higher than 27ºC during working hours. This corresponds to 1 % of the work hours and a frequency of 0.99. On the red curve in figure 5.36 this number can be read to app. 0.98, which is twice the recommended value. The room fails thus also this recommendation.

The work hours in the analysis are in this section of the report defined as Monday to Friday between 8:00 and 17:00 at working days. The measuring period is from July, 1. 2007 to August 31. 2008. This gives a total number of days in the analysis of 428. With measurements each 5 minutes it gives a maximum of 123,264 measurements for each sensor. However there is missing data and for most of the sensors there are between 98,939 and 106,005 observations, corresponding to available data between 80 % to 86 % of the time which is considered to be very satisfactory. The working hours account for only 27 % of the total hours. This is why the curves for other hours and all hours show nearly the same appearance on the curves. In the comparisons it is therefore primarily other hours which are compared with working hours.

The ventilation systems are as seen in section 5.4 running at almost constant volume flow rate during working hours and are switched off during other hours. The cooling system is supposed to be activated if the room temperature is above the set point temperature. The users can adjust the set point temperature ±3 K during working hours while outside working hours the global setting is applied.

There might be minor differences between the data from different rooms due to differences in the amount of missing data.

By comparing the different curves it is possible to characterize the typical indoor temperatures in the different rooms. The aim is to give a characterization of each single room. By this characterization it is possible to extract information about if the room performs typical or it shows an untypical performance. If the profile deviates from other rooms it could be worthwhile to find the reason for this discrepancy. The curves can assist to find the diagnosis in this process.

The following parameters have a major impact on the thermal performance:

- External climate (solar radiation, external temperatures and wind).
    - Some of the rooms are exposed to the external climate giving additional heat load from solar radiation during daytime and heat loss when there are low external temperatures.
- Internal heat sources (equipment, lightning and persons)
    - The internal heat sources give an additional heat load
- Operation of heating, cooling, ventilation and shading system.
- Heat exchange with other rooms (ventilation or conduction through walls, floors and ceilings)
- Heat capacity of the rooms

The building is generally dominated by a considerable amount of internal load – see section 5.3. Therefore the considerations below are specific for this building. Other buildings with lower amount of internal load may perform differently when the thermal performance is evaluated.

Table 5.3 classifies the visual observations from the curves in 11 categories. A plausible explanation of the observations is given for each of these categories. Further an example is given with a reference to a figure and to the rooms which have a similar appearance. The room number in bold corresponds to the room which is shown in the referenced figure.

Category	Observation from curves	Possible explanation	Examples (figure and room numbers)
1	Working hours close to other hours	Small heat load, no cooling, large heat capacity compared to heat load	Fig. 5.37 Room **306**

2	Lower part: Working hours close to other hours Upper part: Working hours lower than other hours	Heat load independent of working hours at lower part. Heat load intermittent at upper part (e.g. solar gain). Cooling at high temperatures or solar shading activated during working hours	Fig. 5.38 and Fig. 5.39. Room **117**, 304, 401, 421
3	All temp. working hours lower than all temp. other hours.	No or permanent heat load. Cooling or ventilation in all working hours. Maybe the temperature sensor is exposed to cold air from the cooling baffles and/or a large heat loss.	Fig. 5.40 Room 301, **302**, 320, 322, 325, 328, 330, 332
4	All temp. working hours larger than all temp. other hours.	Additional heat load during working hours. Cooling or ventilation in all working hours might be insufficient.	Fig. 5.41 Room **313**
5	Curve for temp. working hour's crosses curve for temp. other hours (working hours lowest at upper part of curve)	Significant heat load at working hours. Cooling of rooms at working hours when temperature is higher than a certain level. At the lower part of the curves the horizontal difference between working and other hours indicate the level of thermal load. At the upper part of the curves the horizontal difference between working and other hours indicate the level of cooling load.	Fig. 5.42 Room 307, 309, 316, 317, 318, **324**, 329
6	Curve for temp. working hour's crosses curve for temp. other hours (working hours highest at upper part of curve)	Small heat load at a large part of the working hours but some additional heat load from intermediate sources as e.g. solar gain or many persons at certain times. Cooling or ventilation at all working hours. The cooling or ventilation load is insufficient to cool down the temperatures of rooms at working hours when temperature is higher than a certain level.	Fig. 5.43 Room **327**
7	A number of hours with temperatures lower than the normal set point temperature.	Large heat loss from the room, insufficient heating capacity or low set point temperature.	Fig. 5.44 Room 231, 313, **460**, 518
8	A number of hours with high temperatures during other hours.	Large heat load either permanent or from ambient.	Fig. 5.45 Room 222, 224, **231**, 324, 443, 462
9	Steep curve at normal temperature level	Small heat load or good control function of heating, ventilation or	Fig. 5.46 Atrium, room

		cooling.	**312**
10	Steep curve at high temperature level	The internal load is small or constant (limited solar gains). Maybe a large cooling capacity or ventilation rate.	Fig. 5.47 Room 322, **332**
11	Moderate slope	Large heat load. Poor functioning of the cooling or ventilation.	Fig 5.48 Room 316, **323**, 324

Table 5.3. The table shows possible explanations of certain visual appearances on the cumulated frequency curves.

5.6.1 Individual comments on some of the rooms

Figures 5.37-48 show cumulated frequency curves for the rooms shown in bold in table 5.3 for different rooms.

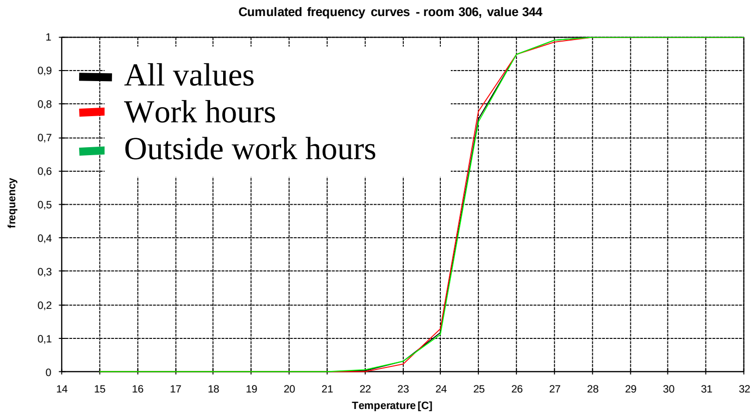


Figure 5.37. Category 1. Room 306. Same temperature level in and outside working hours. Small thermal load.

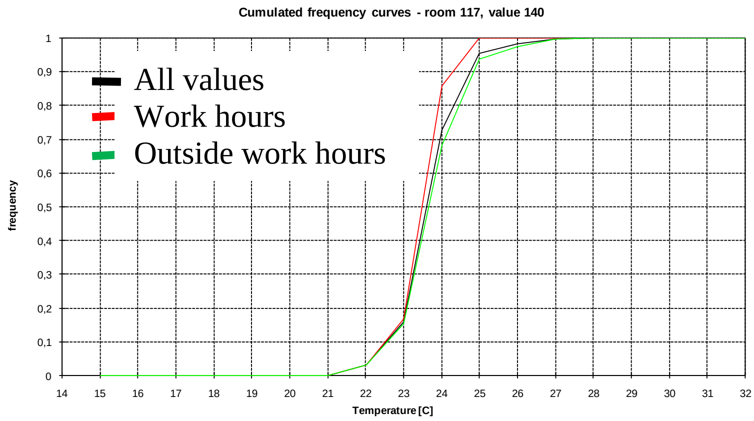


Figure 5.38. Category 2. Room 117. Same temperature level in and outside working hours at low temperatures. At higher temperatures there are fewer hours with high temperatures in working hours than outside working hours.

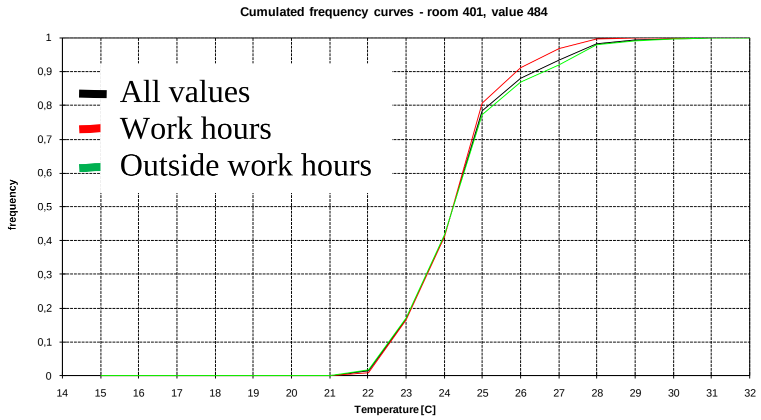


Figure 5.39. Category 2. Room 401. Same temperature level inside and outside working hours at lower part of temperatures. At higher temperatures there are fewer hours with high temperatures in working hours than outside working hours.

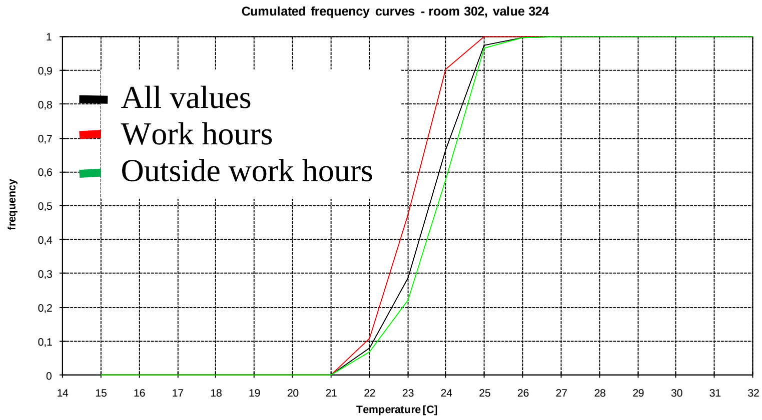


Figure 5.40. Category 3, Room 302. Temperatures in work hours lower than outside working hours. Small heat load. Probably increased ventilation/cooling in working hours or cold air is hitting the temperature sensor.

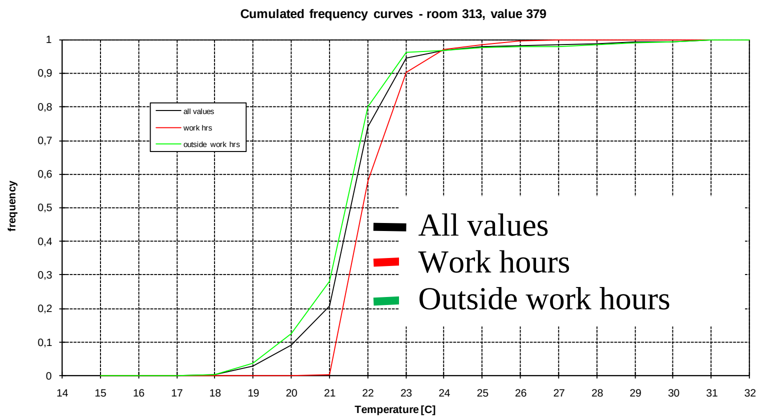


Figure 5.41. Category 4, Room 313. Temperatures in work hours larger than outside working hours (most of the time). Maybe a large heat loss from the room resulting in low temperatures outside working hours. Probably a change in heating set point from working to non working hours. Very few hours with cooling.

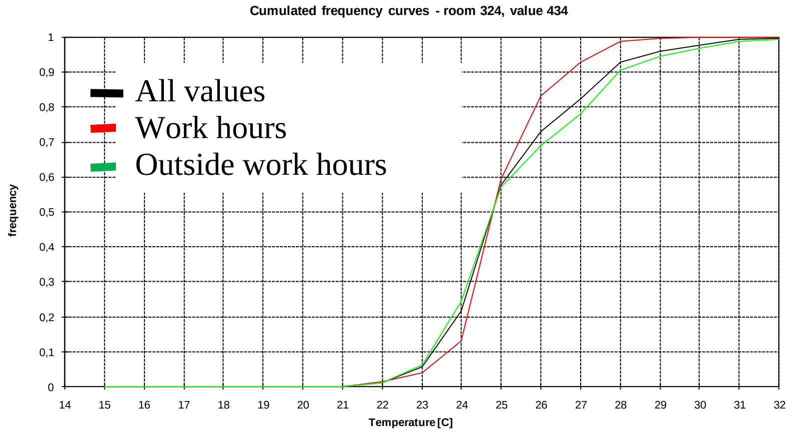


Figure 5.42. Category 5, Room 324. Temperatures in work hours larger than outside working hours in the lower temperature range while the temperatures in work hours are lower than outside the working hours in the upper temperature range. Large heat gains in the room (including large solar gains). There are many hours with cooling in working hours but this is not sufficient to keep the temperature below an acceptable level.

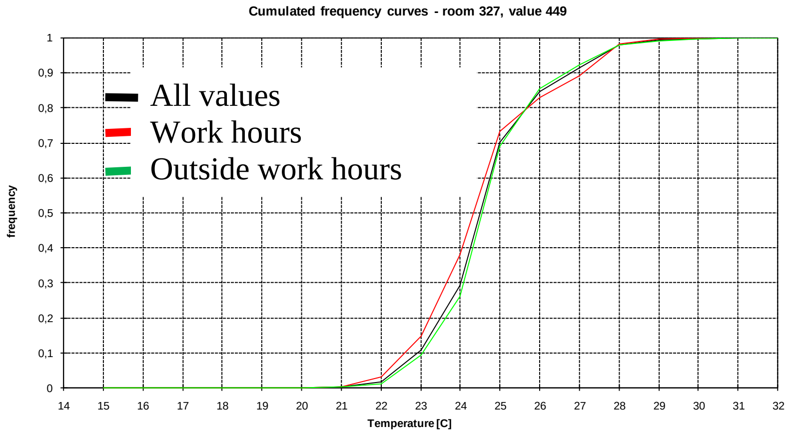


Figure 5.43. Category 6, Room 327. Temperatures in work hours smaller than outside working hours in the lower temperature range while some of the temperatures in work hours are higher than outside the working hours in the upper temperature range. Many hours with high temperatures probably due to large heat gains in the room (including large solar gains). Ventilation in working hours but apparently no or insufficient cooling capacity.

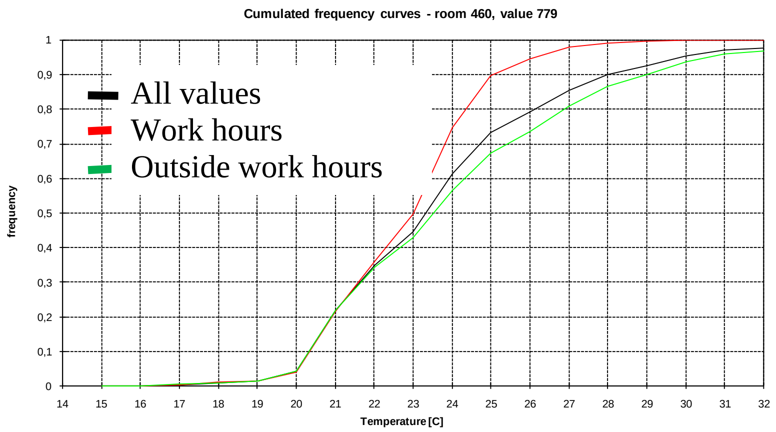


Figure 5.44. Category 7, Room 460. The room size is small and exposed to solar radiation. A number of hours in and outside work hours are in the lower temperature range. Low heating set point or increased heat loss. Cooling in work hours in the upper temperature range.

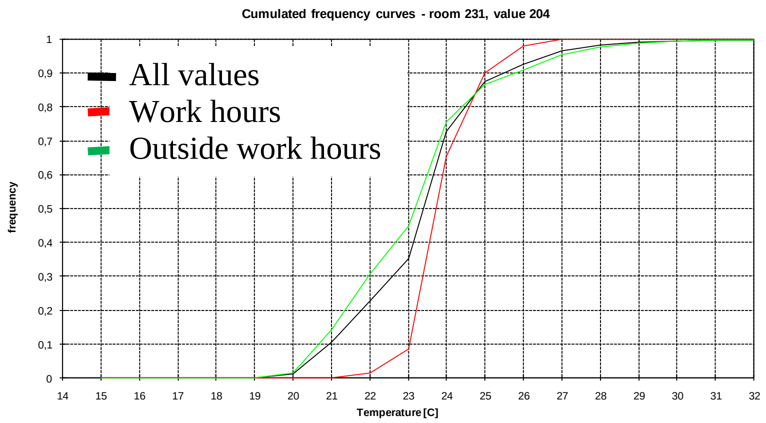


Figure 5.45. Category 8, Room 231. The room is exposed to solar radiation. Temperatures in work hours larger than outside working hours in the lower temperature range while the temperatures in work hours are lower than outside the working hours in the upper temperature range. Large heat gains in the room (including large solar gains). Many hours with cooling which are sufficient to keep the temperature below an acceptable level. Maybe low heating set point outside working hours and high heating set point in working hours. The room has walls towards the exterior which may cause large heat loss and low temperatures during other hours.

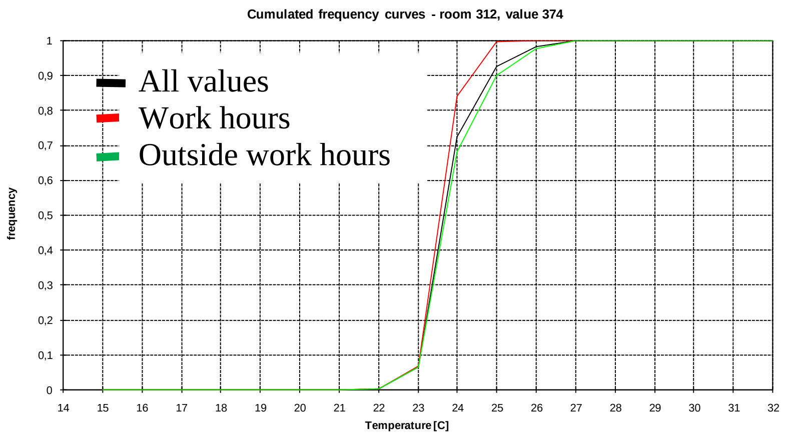


Figure 5.46. Category 9, Room 312. Steep curve at normal temperature level. Small heat load (no or small exposure to solar radiation). Limited number of hours with cooling.

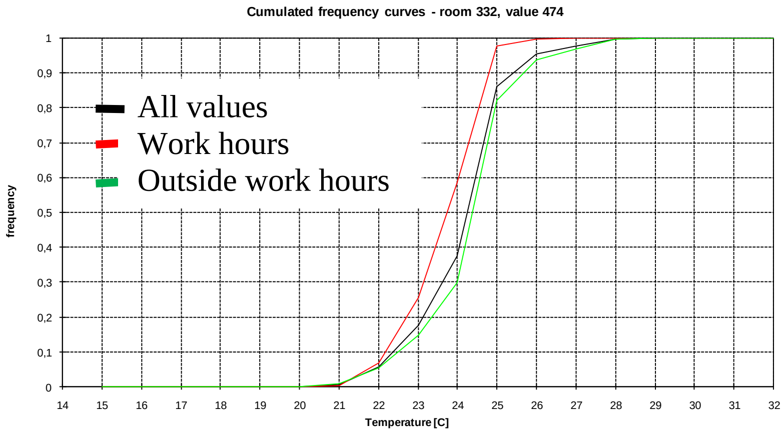


Figure 5.47. Category 10, Room 332. Steep curve at high temperature level. Small heat load (no or small exposure to solar radiation). Ventilation and cooling in working hours reduce temperatures. Maybe the temperature sensor is hit by cold air.

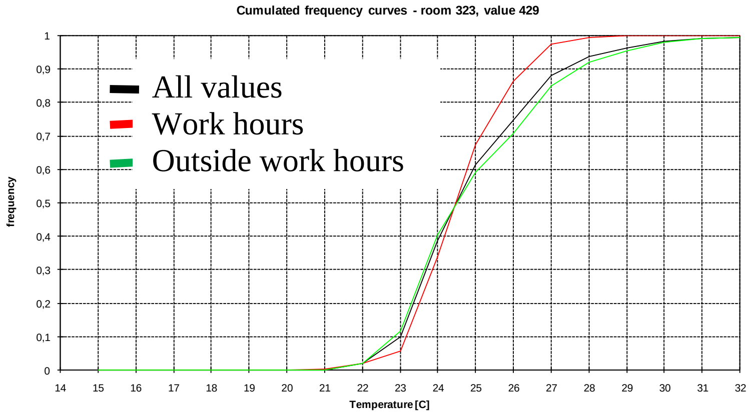


Figure 5.48. Category 11, Room 323. Moderate slope of the curve. Indications of large heat load (exposed to solar gain). Indications of small ventilation (or increased heat load) in working hours in the lower part of the temperature range. Cooling in the upper part of the temperature range but insufficient to obtain acceptable temperatures.

5.6.2 Suggestions for possible actions to be taken

A set of curves like the ones presented could be produced at certain intervals e.g. once a year or as updated curve each month which may be compared with other curves for instance curves from the previous year. The main purpose is to see whether the comfort level in each of the rooms are acceptable in general or if any parameters should be modified either to improve the comfort level or in order to save energy.

The first concern from the curves is if the temperature level is in an acceptable range. Some of the rooms have temperature levels which are not acceptable with regard to human thermal comfort but these rooms might be server rooms and other rooms with a special use. These rooms should be taken out of the general evaluation unless the rooms are expected to significantly influence the temperatures of other rooms. However the temperature level might indicate that there is a large heat load and a corresponding energy consumption which might be considered separately.

The rest of the rooms selected are then evaluated in terms of thermal comfort.

In the next section (5.6.3) is shown how it by assistance of the BMS-system has been identified rooms with higher temperatures than normally accepted.

These rooms should be given a high priority in the evaluation. The curves for the rooms should be categorized in relation to the table elaborated above. This will give some information about the possible reason for the unacceptable temperature levels. In the same way rooms with acceptable temperature levels should be classified according to the table in order to identify if energy savings might be possible. The considerations are illustrated in the flowchart below:

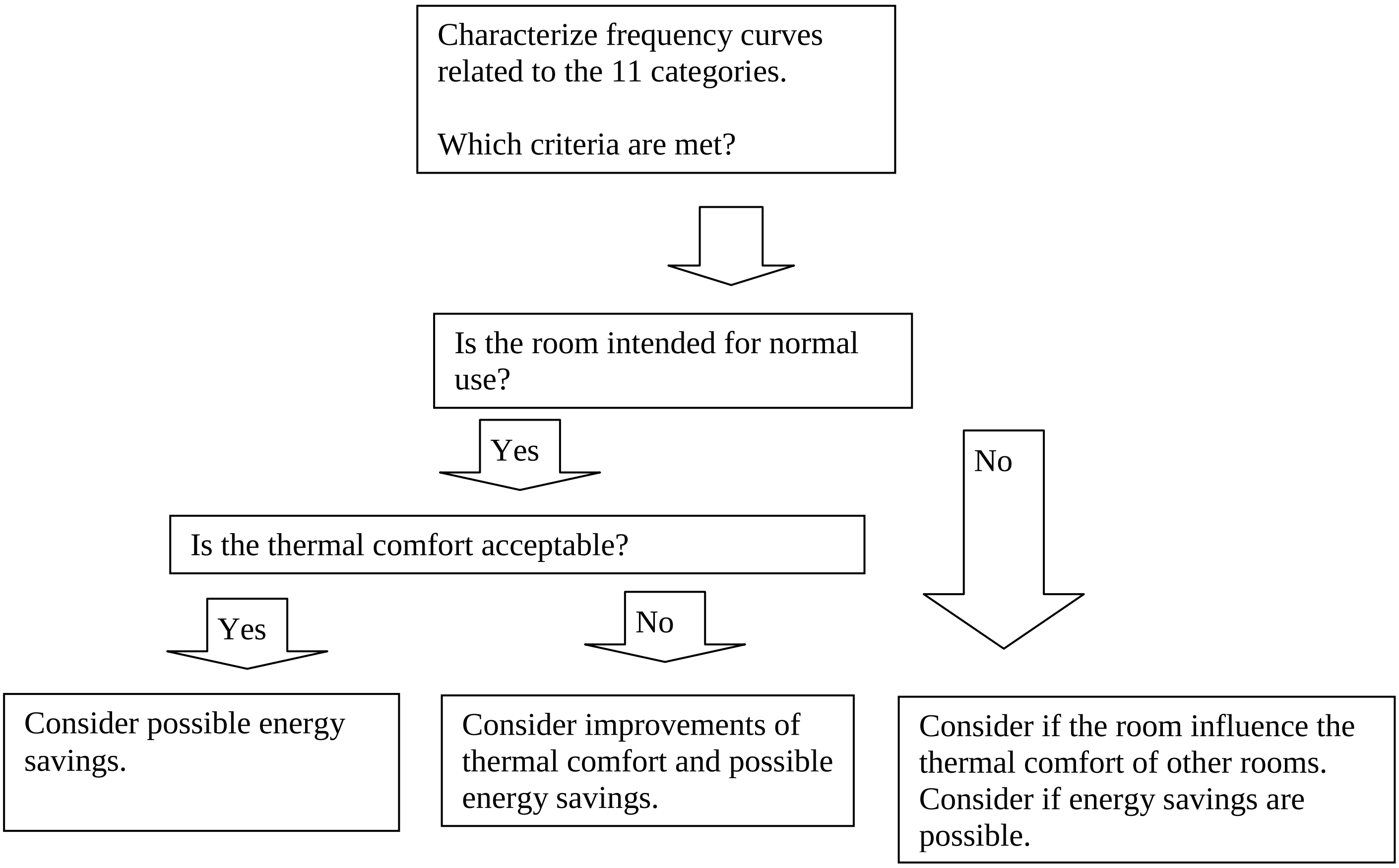


Figure 5.49. Flowchart showing possible considerations to be made in order to categorize and find potential problems regarding thermal comfort and energy consumptions.

Below are some considerations concerning possible actions to be taken for each of the categories in table 5.3 and the flowchart in figure 5.49. The considerations are specific for the building investigated (Tuborg Boulevard 12) which is characterized by a large heat load.

Cate-gory	Observation from curves	Thermal comfort acceptable (considerations concerning energy)	Thermal comfort not acceptable (considerations concerning thermal comfort and energy)
1	Working hours close to other hours	Probably limited possibilities for energy savings. When the curves are close it indicates small heat loads and limited cooling.	Cooling, night cooling or increased ventilation could be applied
2	Lower part: Working hours close to other hours Upper part: Working hours lower than other hours	Consider if there is too much cooling or ventilation. (figure 5.39)	Increased cooling or ventilation or reduction of heat load (figure 5.40)
3	All temp. working hours lower than all temp. other hours.	Consider if there is too much cooling or ventilation	Increased cooling or ventilation or reduction of heat load
4	All temp. working hours larger than all temp. other hours.	Probably limited possibilities for energy savings. The curves are close. It indicates small heat loads and limited cooling.	Increased cooling or ventilation or reduction of heat load
5	Curve for temp. working hours crosses curve for temp. other hours (working hours lowest at upper part of curve)	Consider if there is too much cooling or ventilation	Increased cooling or ventilation or reduction of heat load
6	Curve for temp. working hours crosses curve for temp. other hours (working hours highest at upper part of curve)	Probably limited possibilities for energy savings, but heating load might be reduced.	Increased cooling or ventilation or reduction of heat load
7	A number of hours with temperatures lower than the normal set point temperature.	Consider if there is to large heat losses from the room	Increased heating and also consider if there is to large heat losses from the room
8	A number of hours with high temperatures during other hours.	Consider if the heat load can be reduced.	Consider if the heat load can be reduced
9	Steep curve at normal temperature level	Consider if there is too much cooling or ventilation	Consider if the heat load can be reduced
10	Steep curve at high temperature level	Consider if there is too much cooling or ventilation	Consider if the heat load can be reduced or the cooling set point is correct.
11	Moderate slope	Consider if the heat load can be reduced.	Consider if the heat load can be reduced or more cooling is needed

Table 5.4. The table shows possible considerations and actions to be taken on the basis of the visual observations from the accumulated frequency curves.

The analysis leads to the following proposals:

- cold air from the cooling baffles should be prevented from directly hitting the temperature sensors of the BMS
- solar shading devices – preferably external – should be applied in rooms with large thermal load from the sun
- for all the rooms in the building the procedure described above should be implemented.
- the rooms should be categorized according to the tables.
- for each room it should be considered if it is relevant or not to introduce some changes regarding thermal comfort or energy savings.
- after a period e.g. 1 year the analysis could be done again or updating of the curves could be done frequently and compared with the previous year.
- for the room where it was decided not to take actions it could automatically be analyzed if the frequency curves are similar to the previous analysis and hence no further actions should be taken.
- if the rooms show a different behavior the rooms should be analyzed and categorized again to see if some actions should be recommended.
- the rooms for which some actions have been taken it should be analyzed if it has resulted in improvements concerning thermal comfort or energy savings.

In all cases it could be considered if the set point for heating outside some of the working hours could be lowered or if this will provide problems. It is observed that there are very few hours with temperatures lower than the set point in the working hours.

5.6.3 Average temperatures in the rooms operated by the different ventilation systems

In figure 5.50 is shown and compared the cumulated frequency curves of average temperatures for rooms operated by the different ventilation systems.

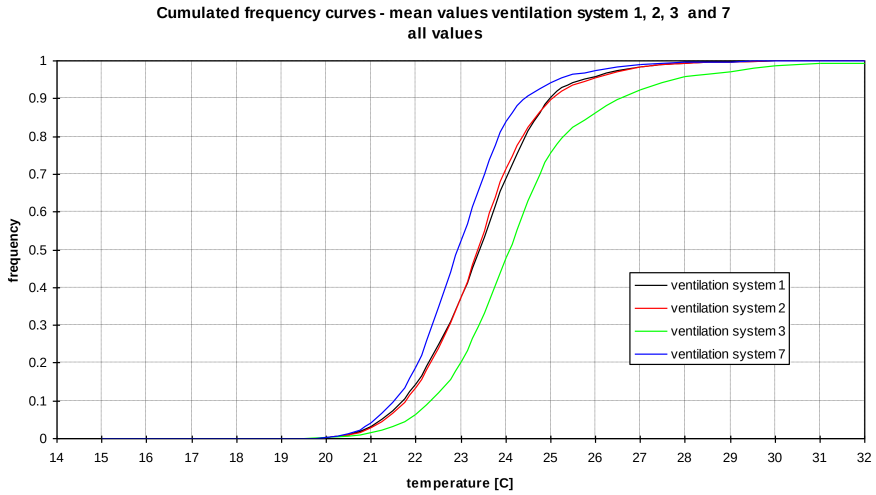


Figure 5.50. Cumulated frequency curves of the average room temperatures for the 4 ventilation systems (1, 2, 3 and 7). The data is based on measurements from the BMS system.

The average temperatures for ventilation system 1 and 2 are nearly identical, while the average temperatures for ventilation system 7 are lower and higher for ventilation system 3.

For the measurement period of a little more than one year the number of hours, based on these average curves, with high temperatures is estimated to be:

Ventilation system	Hours with > 26°C	Hours with > 27°C
1	34	9
2	53	10
3	167	73
7	3	0

Table 5.5. Number of hours where the average temperatures exceeds 26°C and 27°C for each of the four ventilation systems. (BMS data).

It must be noted that the result might be different if the estimate is based on the average of the numbers of exceeding hours for each of the rooms. Considering only the averages all the ventilation systems except ventilation system 3 fulfill the demands in (SBi, 2000). For the reason of comparison the number of hours with exceeding temperatures is also estimated based on the measurements from the special purpose indoor climate data loggers – chapter 4. The data however covers a shorter period and fewer rooms, therefore the number of hours is adjusted to correspond to the number of observations from the BMS-system. Even if this gives an uncertainty there is reasonable agreement concerning the exceeding temperatures found by the two sets of data.

Ventilation system	Hours with > 26°C	Hours with > 27°C
1	0	0
2	81	34
3	212	49

Table 5.6. Number of hours where the average temperatures exceed 26 °C an 27 °C for each of the three ventilation systems (from the special purpose indoor climate data loggers – chapter 4).

Figure 5.51 shows the cumulated frequency curves for ventilation system 1-3 with data from the indoor climate data loggers (chapter 4).

The data from the special indoor climate data loggers (figure 5.51) shows a temperature approximately 1-1.5 K higher than the data from the BMS system (figure 5.50). This difference is considered to be acceptable as the measurements of the special purpose data logger are from the working zones while the BMS data are measured close to walls. This difference is discussed earlier in section5.2.

However, the difference of 1-1.5 K between the two types of measurements explains why fewer indoor climate problems are found in chapter 4 than in the present chapter. It is therefore important both for the indoor climate in the rooms and for the use of frequency curves that the BMS measurements are representative of the room temperatures.

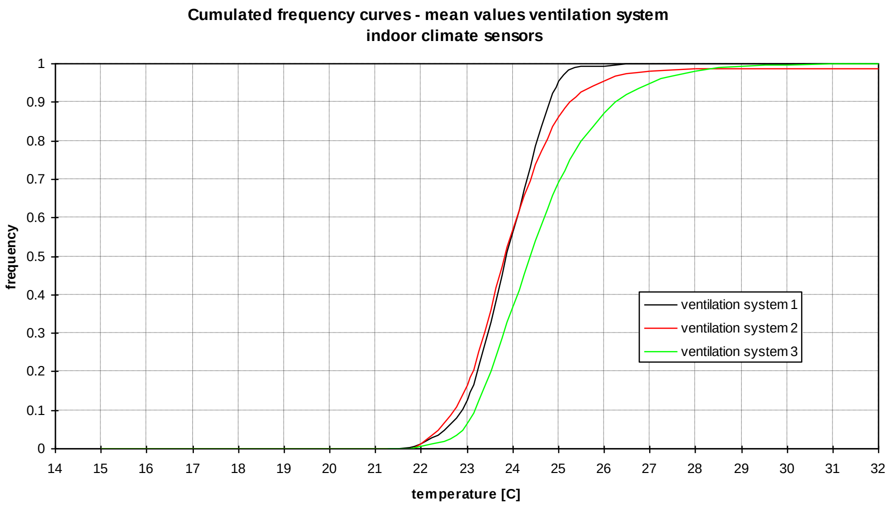


Figure 5.51. Cumulated frequency curves of average temperatures for the 3 ventilation systems (1, 2 and 3). The data is based on measurements from the special purpose indoor climate data loggers.

5.6.4 Room temperatures from the single rooms operated by the different ventilation systems

Below are shown cumulated frequency curves for the rooms served by ventilation system 1, 2, 3 and 7.

The curves for ventilation system 1 and 2 (figures 5.52 and 5.53) are seen to have the same appearance regarding the slope (shape) of the curves and are therefore looking nearly parallel to each other. A plausible explanation might be different heating set points in the rooms.

When all the curves from the four ventilation systems are compared it is seen that many of the rooms served by ventilation system 3 (figure 5.54) have larger overheating problems than rooms serverd by the other ventilation systems. It can also be seen that the shape of the curves for the rooms served by ventilation system 3 are different and that many of these rooms have a moderate slope indicating a large heat gain or an insufficient cooling system.

The curve for room 328 in figure 5.54 deviates significantly from the other curves. This room was in section 5.4 found to the room with the largest overheating problems. However, it is easier to see this in figure 5.54 than in Appendix 5, which indicates that frequency curves of the room temperatures are a powerful tool when evaluating the thermal comfort.

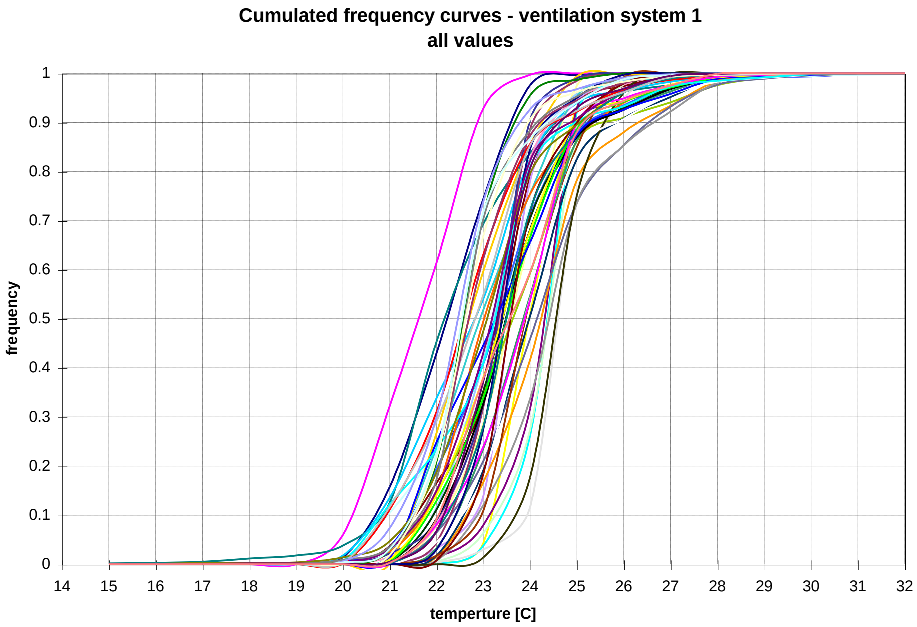


Figure 5.52. Cumulated frequency curves of all room temperatures for ventilation system 1. The data is based on measurements from the BMS system.

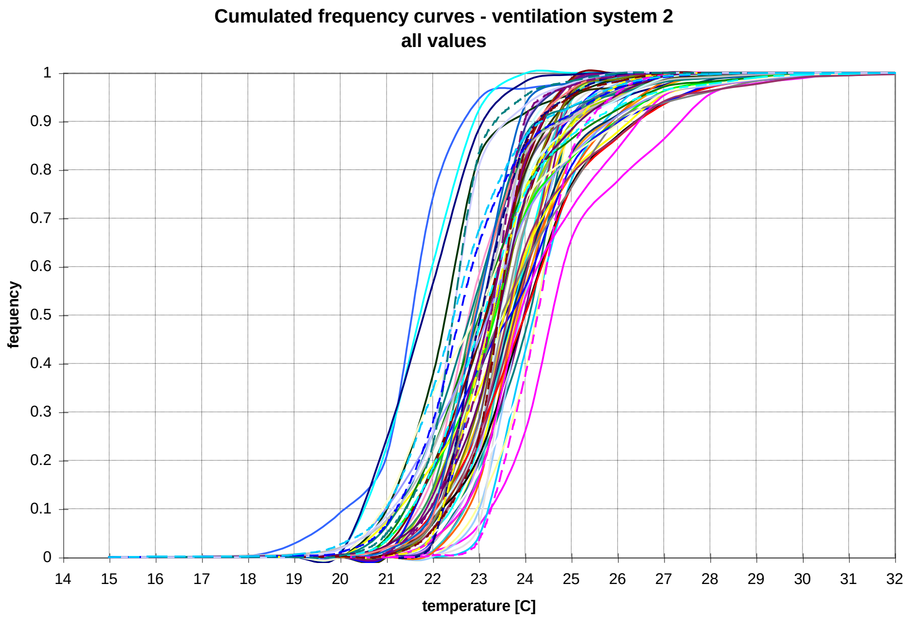


Figure 5.53. Cumulated frequency curves of all room temperatures for ventilation system 2. The data is based on measurements from the BMS system.

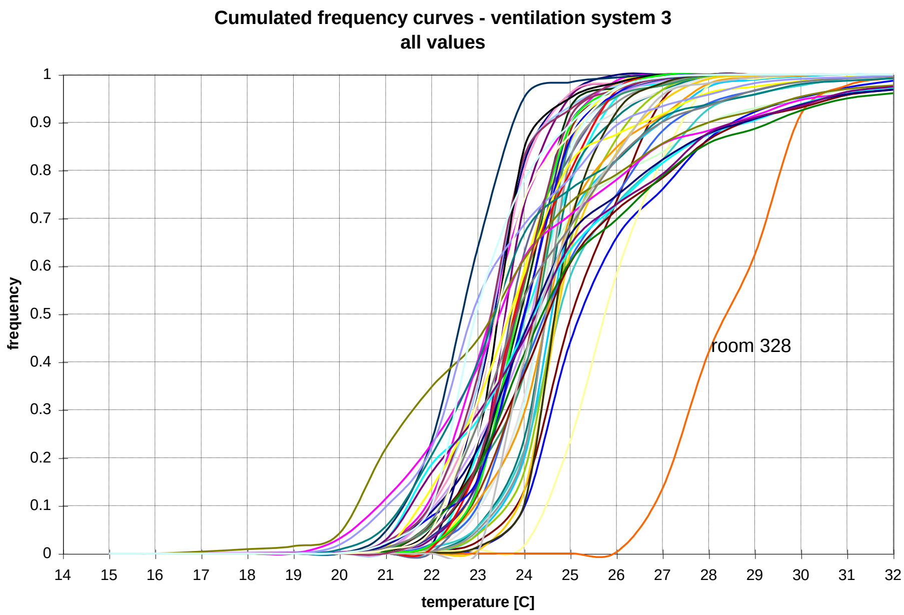


Figure 5.54. Cumulated frequency curves of all room temperatures for ventilation system 3. The data is based on measurements from the BMS system.

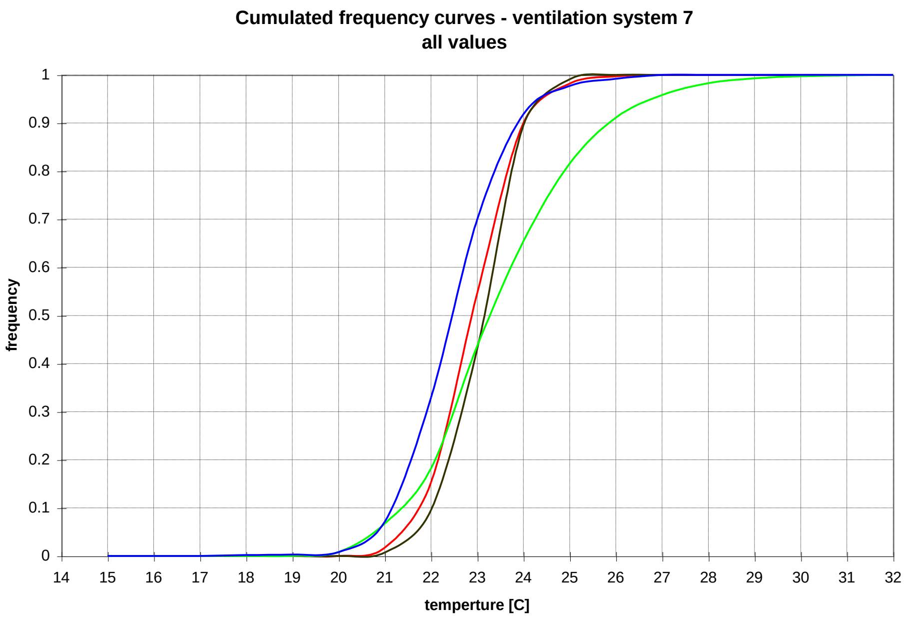


Figure 5.55. Cumulated frequency curves of all room temperatures for ventilation system 7. The data is based on measurements from the BMS system.

The temperature profile of the *atrium* for workings hours is the same as in other hours (figure 5.56). The slopes of the curves are steep curves without overheating. This leads to the expectation that the atrium is very well regulated in terms of comfort. But an atrium has an energy consumption due to floor heating and due to heating beneath the roof in order to prevent cold draughts. This is discussed further in section5.7.

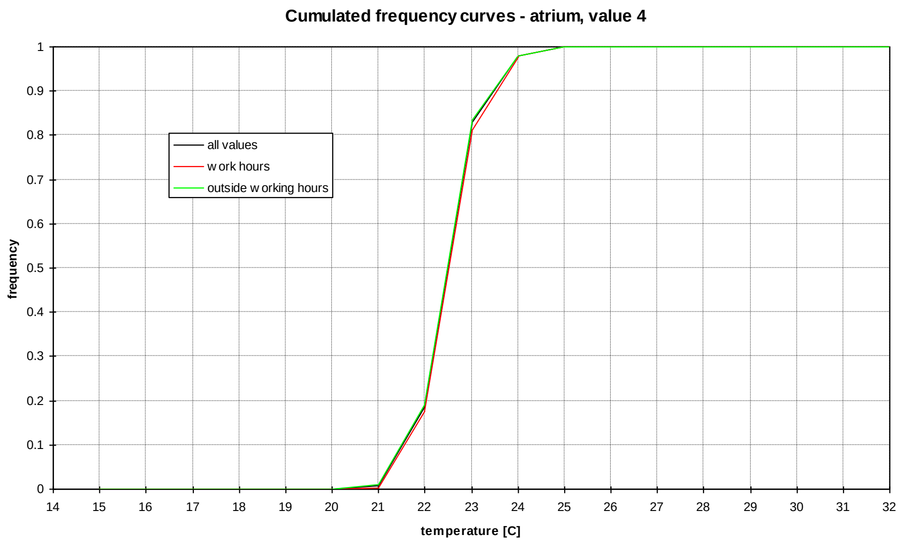


Figure 5.56. Cumulated frequency curves of temperatures in the atrium. The data is based on measurements from the BMS system.

5.6.5 Temperature distribution for the rooms

The cumulated frequency curves for all the rooms registered in the BMS system were screened to determine which rooms do not fulfill the demands in (SBi, 2000) – see also the discussion of figure 5.36. The results from the analysis show the number of rooms with indoor climate problems. The result in table 5.7 is the number of rooms with and without problems divided by ventilation system and by the floor number of the building.

	total number of rooms	rooms with okay temp.	rooms with problems	rooms with problems		
				Vent1	Vent2	Vent3
Ground floor	11	10	1	0	1	0
1st floor	31	27	4	0	0	4
2nd floor	33	26	7	1	0	6
3rd floor	62	40	22	5	8	9
4th floor	33	30	3	0	2	1
total	170	133	37	6	11	20

Table 5.7. Number of rooms with problems which means that the temperatures are above the limits in (SBi, 2000). The problematic rooms are distributed according to floors and ventilation systems.

Table 5.7 shows that 37 out of the 170 rooms (or 22%) do not fulfill the temperature recommendations in (SBi, 2000).

The result of the frequency analysis of the room temperatures is shown graphically in figure 5.57. All rooms were assigned a color according to the following criteria's:

green: Room temperatures exceed 26^{o}C *less* than 100 hours *and* exceed 27^{o}C *less* than 25 hours.

orange: Room temperatures exceed 26^{o}C *more* than 100 hours *or* exceed 27^{o}C *more* than 25 hours.

red: Room temperatures both exceed 26^{o}C *more* than 100 hours *and* exceed 27^{o}C *more* than 25 hours.

It must be noted that even if the measured temperatures are within these limits it is not necessarily synonymous with an acceptable indoor climate. Considerations are not taken to local temperature variations, temperature gradients and draught problems.

Of the general tendencies seen in table 5.7 it can be seen that:

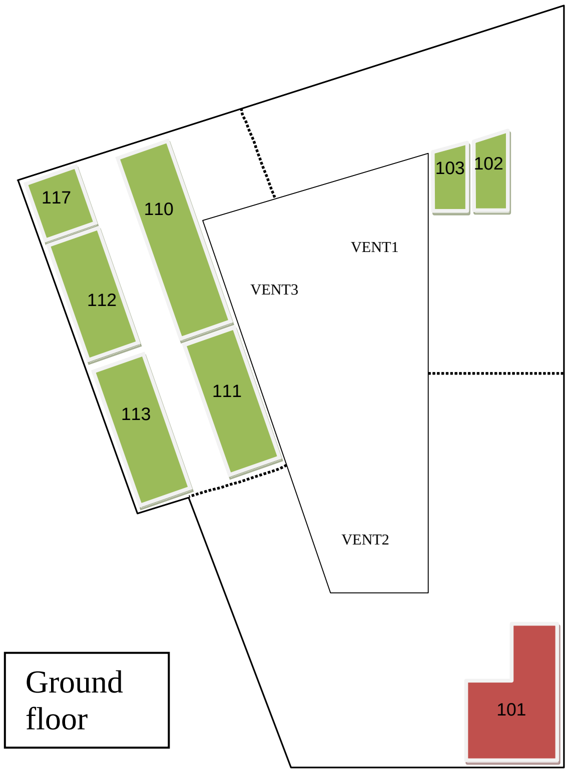
- the largest areas with problems are located in the north western part which is served by ventilation system 3.
- the problems are largest on 3th floor
- ventilation system 3 has problems with high room temperatures on all floors except on the ground floor.
- ventilation system 2 has only significant problems with keeping an acceptable temperature on 4th floor.
- a large part of the rooms with problems are located along the facades, primarily the west and east facades.

5.6.6. Conclusion

The cumulated frequency curve based on historical temperature data is above demonstrated as an effective tool in order to easily get an overview of the situation regarding the thermal comfort level and the operation of a building.

It can be developed further to be a tool which automatically surveys the building and which can give an alarm when the mode of operation is beginning to change.

The method is not fully developed. It requires gathering of experience and development of an automatic tool but can be seen as a step on the road to obtain a more advanced surveying tool for the benefit of both the thermal comfort and the reduction of the energy consumption.



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Ground floor

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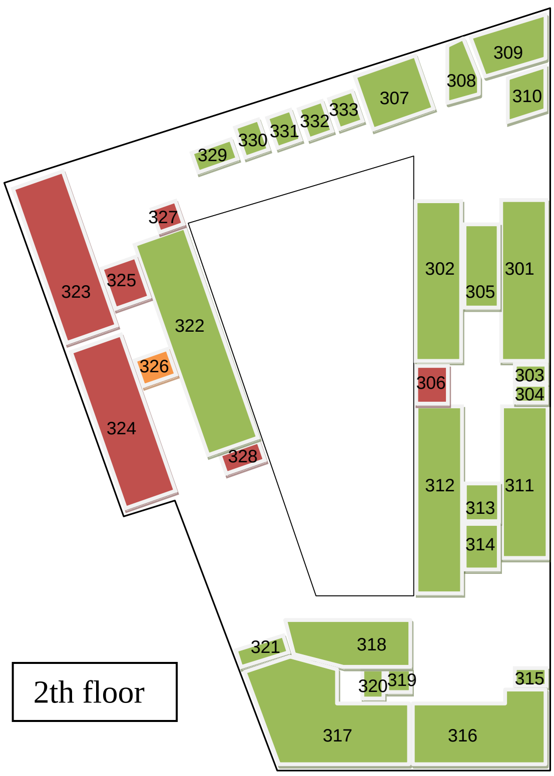
1th floor



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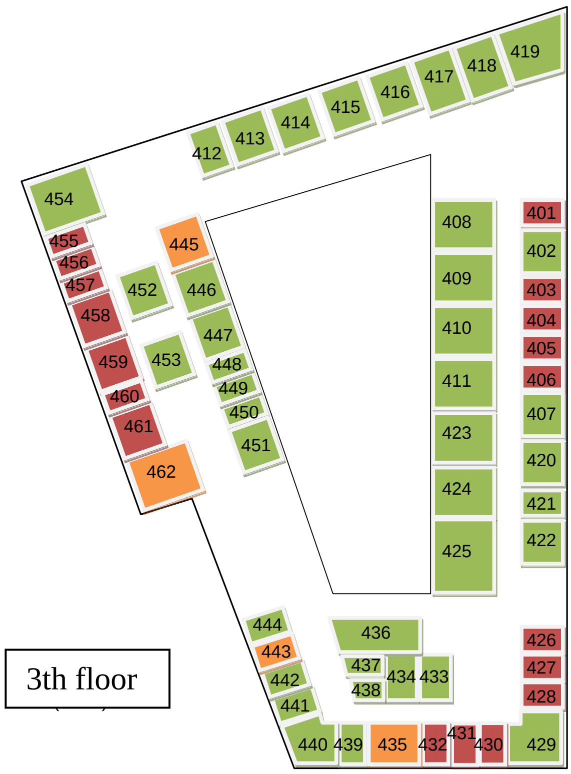

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3th floor

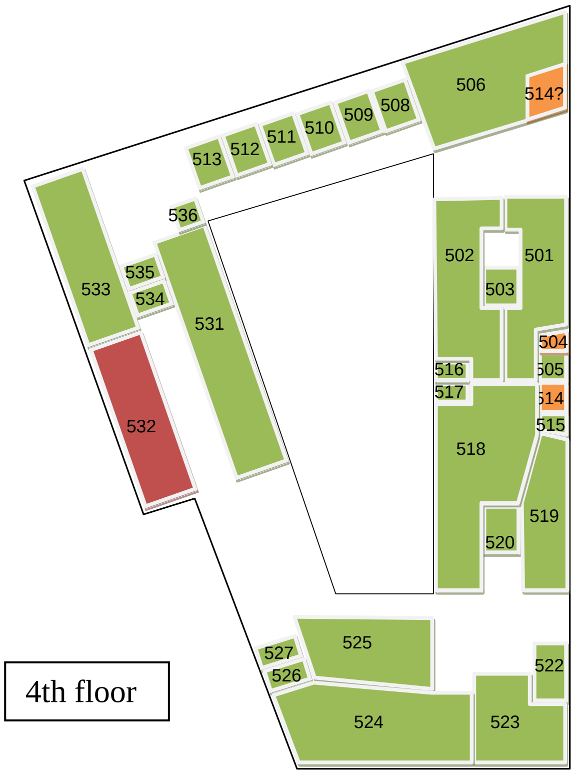


Figure 5.57. Locations of rooms where the temperatures exceed the thermal comfort criteria in (SBi, 2000). Green marks the criteria is not exceeded. Orange marks that one criterion is exceed and red marks that both criteria are exceeded.

5.7. The atrium

Figure 5.58 shows logged values of importance for the atrium.

Explanation of the graphs:

Figure 5.58:	top graph:	blue curve:	air temperature in the occupied zone of the atrium
		red curve:	supply temperature to the floor heating system
		green curve:	ambient air temperature
	second graph:	blue curve:	% opening of the valve for the floor heating system
	third graph:	blue curve:	supply temperature to the convector tubes under the glazed ceiling
		red curve:	set point: ambient temperture at which heating from the convector tubes starts
		green curve:	ambient temperature
	bottom graph:	blue curve:	% opening of the valve for the convector tubes

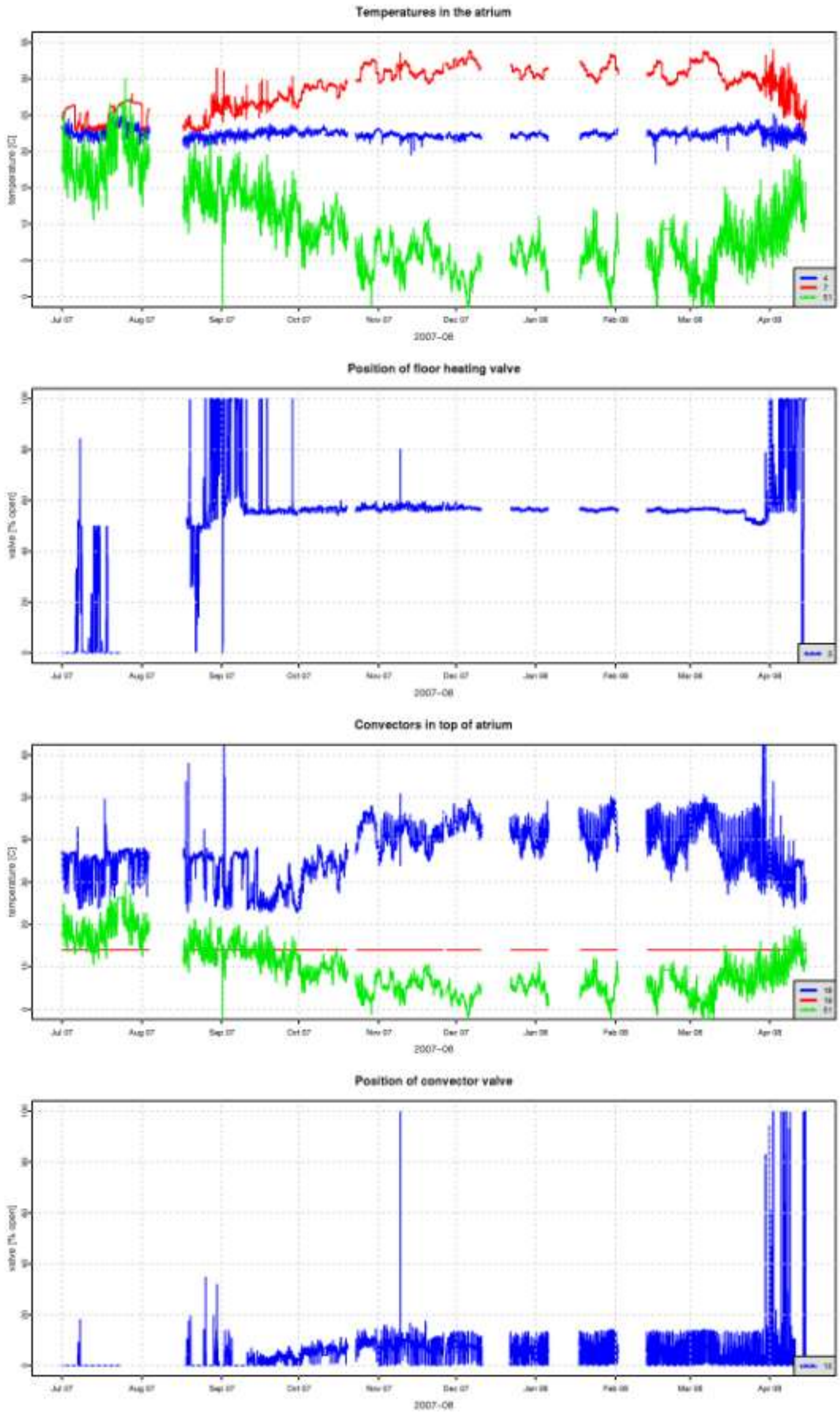


Figure 5.58. Logged values of importance for the atrium.

In section 5.6 it is shown that the atrium is the best tempered zone of the building. Figure 5.58 shows that the air temperature in the occupied zone is quite stable around 22°C. An atrium is often regarded as a circulation zone where there is not the same comfort demand as in the working zones. It is therefore thought-provoking that it is the atrium, which has the best indoor environment. It will be possible to save energy if the atrium was allowed to be more free floating – i.e. allow a lower temperature during the winter. There is no point in having a higher temperature during the summer as the atrium is naturally cooled by opening of windows in the ceilings and in the bottom of the atrium. However, the atrium is now acting as a part of the canteen as seen in figure 2.7 and it is doubtful if the people in the building will allow that this recreational space is taken from them during the winter.

A very rough estimate states that 5-10 MWh/year may be saved by lowering the temperature of the atrium with 1 K during the heating season.

Figure 5.58 shows large fluctuations of especially the valve in the floor heating system in the transition periods – spring and autumn. Figure 5.59 shows a zoom in of figure 5.58 so that only April 2008 is shown. Figure 5.59 shows that the fluctuations of the floor heating valve are mainly a daily variation. This also goes for the convector valve during the transition period while the fluctuations are much more rapid during the stable heating season. Figure 5.60 shows the measured and calculated supply temperatures to the convector tubes under the ceiling of the atrium. As can be seen: the supply temperature calculated by the BMS is a smooth curve. This suggests that there are problems with the regulation of the supply temperature or that the temperature sensor is not located optimally.

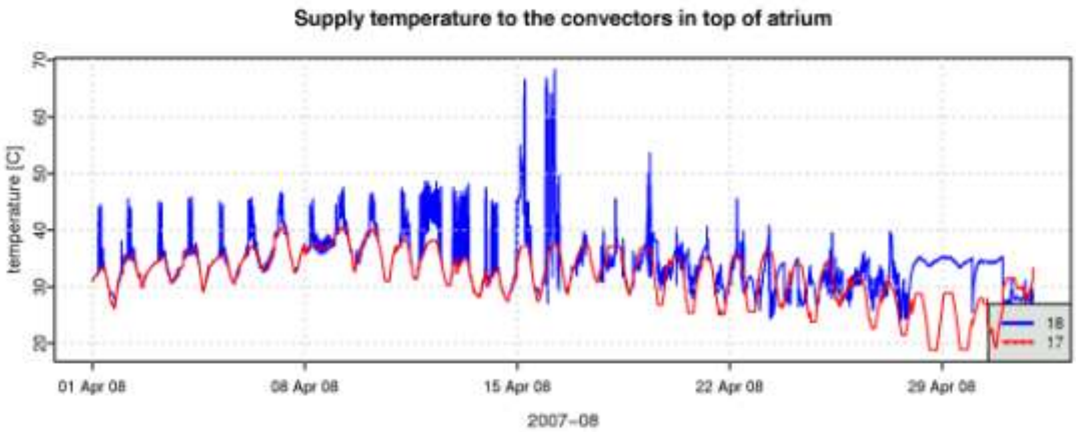


Figure 5.60. The measured and calculated supply temperature to the convector tubes under the ceiling of the atrium. Red curve: calculated (desired) supply temperature, blue curve measured supply temperature.

Figure 5.61 shows the measured and calculated supply temperature to the convectors tubes under the ceiling in the atrium as a function of the ambient temperature. The red curve is the original set point line in the BMS. The curves in figure 5.62 are based on smoothed 15 minutely values in order to obtain the same time stamp on the values on both axis. Figure 5.61 shows that the calculated supply temperature has been reduced by 20 K which is good as a lower supply temperature leads to reduced energy use. Figure 5.61 further shows that the measured supply temperature is identical to the calculated (intended) supply temperature at ambient temperatures below 10°C while it is about 10 K higher at ambient temperatures above 10°C.

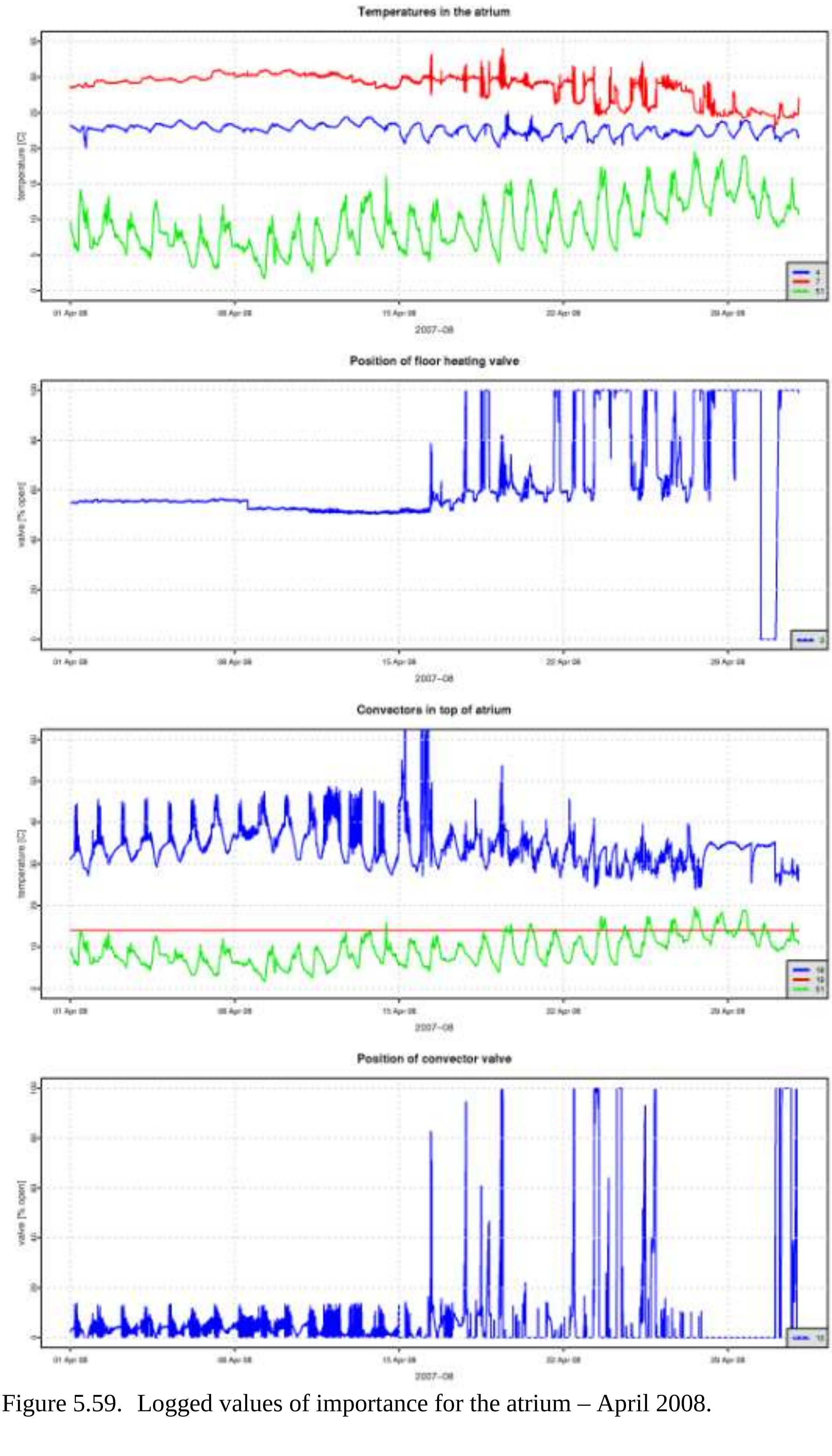
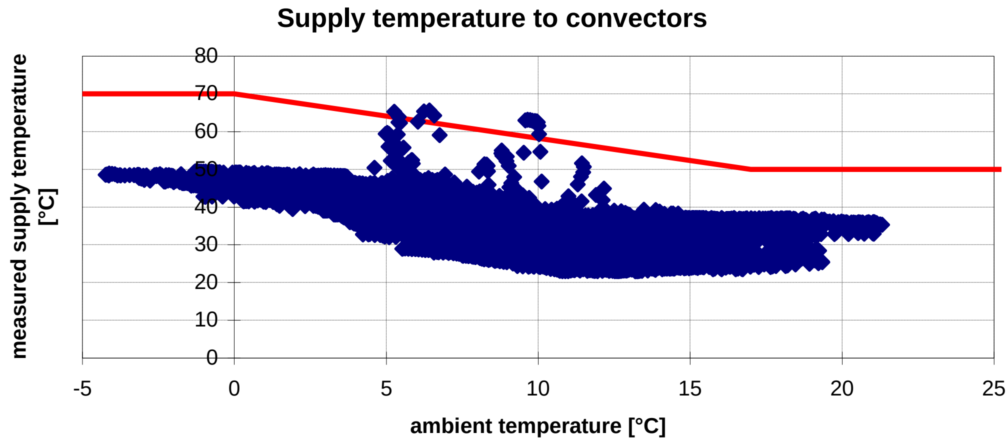


Figure 5.59. Logged values of importance for the atrium – April 2008.



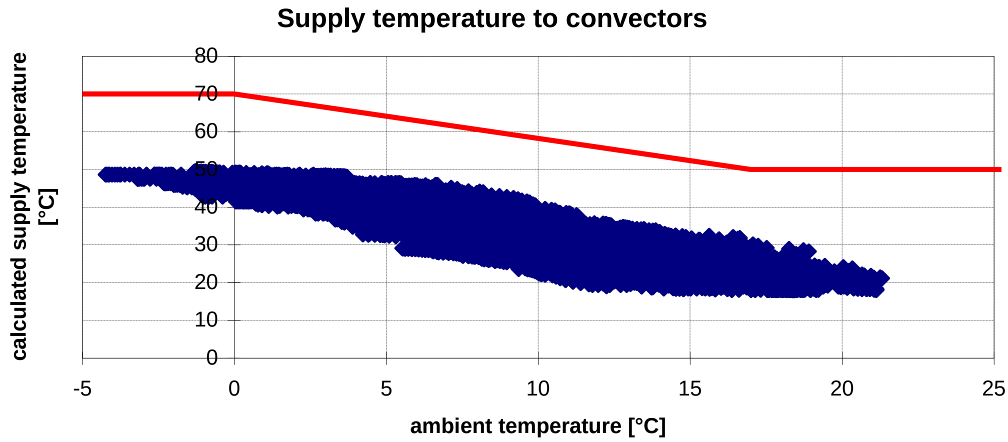


Figure 5.61. Measured and calculated supply temperature to the convector tubes under the ceiling in the atrium. The red line is the original set point line of the BMS.

Figure 5.62 shows the measured and calculated supply temperatures to the floor heating in the atrium as a function of the ambient temperature – there are less logged values for the calculated supply temperature than for the measured supply temperature. This is why there is no values above an ambient temperature of 22°C for the calculated supply temperature. The curves in figure 5.62 are based on smoothed 15 minutely values in order to obtain the same time stamp on the values on both axis. The red curve is the set point line in the BMS. Figure 5.62 shows a good agreement between the set point line in the BMS and the measured and calculated supply temperature.

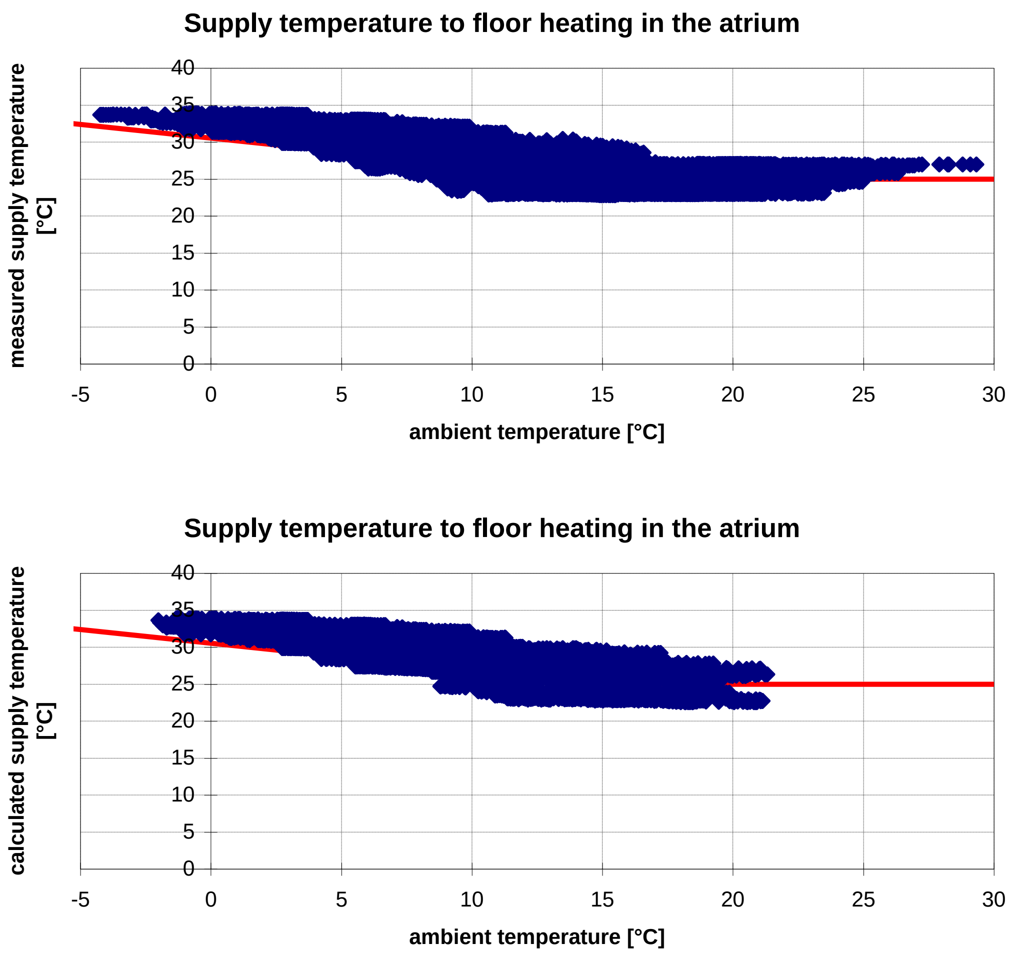


Figure 5.62. Measured and calculated supply temperature to the floor heating in the atrium. The red line is the set point line of the BMS.

Above it is seen that the passive cooling of the atrium can maintain a comfortable temperature in the atrium during warm and sunny periods. Besides opening of windows curtains can also be drawn across the atrium right under the roof lights as seen in figure 2.12. Logged data for these two systems are unfortunately only available for a short period in July-August 2007. This is, however, not a big problem as figure 5.58 shows that the windows/curtains are able to maintain a comfortable temperature. Figure 5.63 shows results from one week in July 2007.

Explanation of the graphs:

Figure 5.63:	top graph:	blue curve:	air temperature in the occupied zone of the atrium
		red curve:	air temperature in the top of the atrium
		black curve:	ambient air temperature
		green curve:	not relevant here
	second graph:	blue curve:	% closing of the curtains (1 = closed)
	third graph:	blue curve:	% opening of the windows in the ceiling (1 = open)
	bottom graph:	blue curve:	global solar radiation

red curve: external lux - when the lux exceeds 1000 lux/10 it goes in zero

weekend: July 22-23

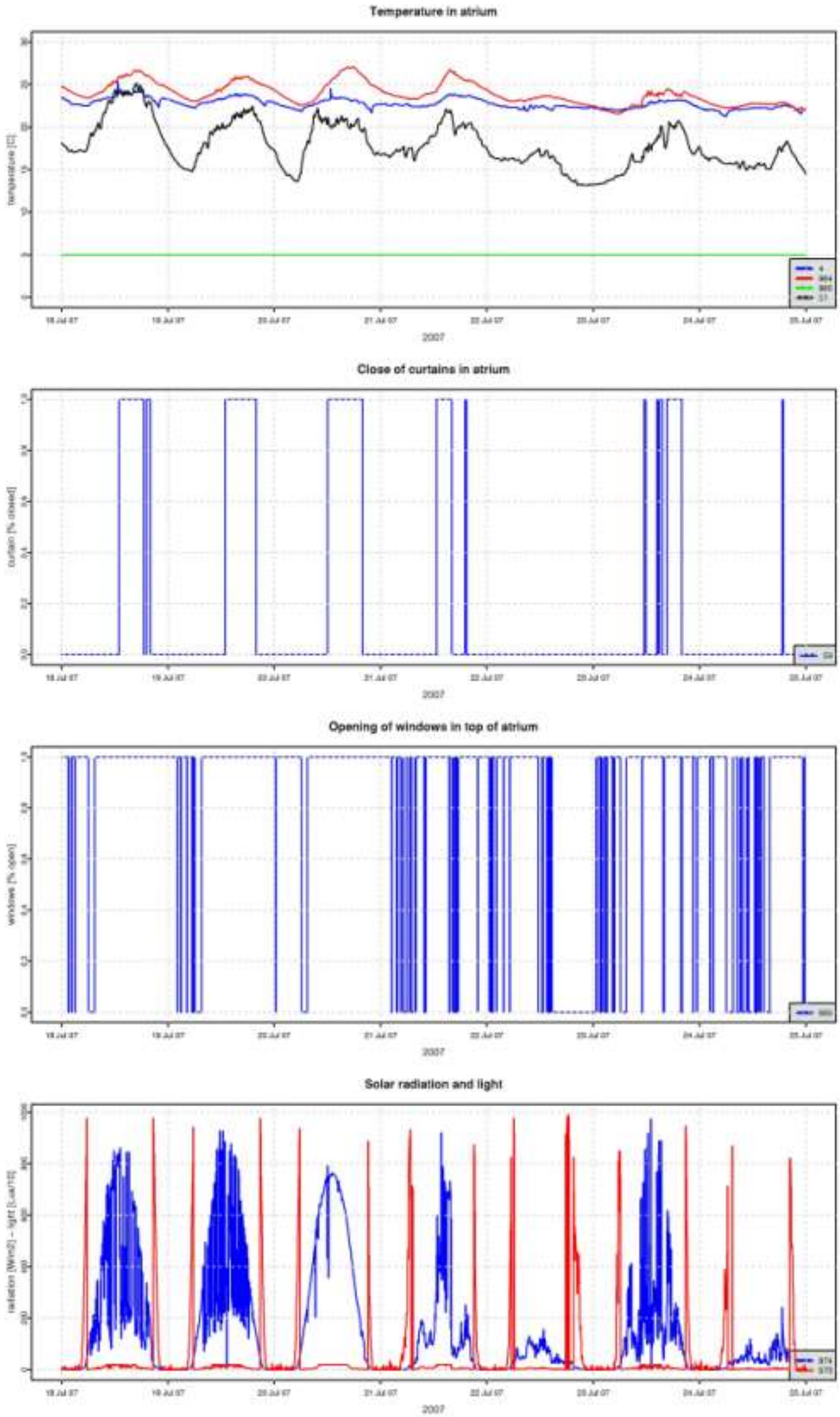


Figure 5.63. Logged data for the curtains and roof ligths of the atrium.

The third graph in figure 5.63 shows that the windows are open a main part of the time – the fluctuations are most probably due to the wind. Excessive night ventilation is thus necessary in order to maintain the comfortable temperature in the atrium. The curtains are closed during periods with large solar radiation level. However it is not - based on the logged data (ie. the lux goes in zero at large lux levels) - possible to investigate if the control of the curtains is appropriate.

Figure 5.63 shows a rather low temperature stratification of max 5 K (the temperature at the top minus the temperature in the occupied zone) which again illustrates the good cooling capacity of the natural ventilation of the atrium.

Based on the investigations it can be concluded that:

- the opening of windows in the roof and at the bottom of the atrium can maintain a comfortable temperature level in the atrium during the summer
- the atrium is the best tempered zone in the building. Energy savings can be obtained by lowering the temperature in the atrium during the heating season
- fluctuation of the opening of the heating valve for the convector tubes under the ceiling should be investigated and if possible be changed to a more smooth regulation

5.8. The radiator system

A screen dump from the BMS concerning the radiator system is shown in figure 3.2. Figures 5.64-66 show logged data for the radiator system.

Figure 5.64-66	top graph:	blue curve:	min room air temperature found by BMS*
		red curve:	set point: max room temperature
		green curve:	set point: min room temperature
	second graph:	blue curve:	supply temperature to the radiators
		red curve:	ambient temperature
		green curve:	set point: ambient temperature at which the heating starts/stops
	bottom graph:	blue curve:	% opening of heating valve

* min room temperature is a fictive temperature series logged by the BMS. The BMS takes for each time step the room temperature from the room with the lowest room temperature.

Figure 5.67 shows measured and calculated supply temperatures to the radiators as a function of the ambient temperature. The red lines in figure 5.67 are the original set points for the supply temperature to the radiator system. These are defined as:

70°C at ambient temperatures below -12°C
25°C at ambient temperatures above 17°C
linear dependency on the ambient temperature between -12 and 17°C

Figure 5.64 shows 6 outliers of the min room temperature (ie values of 0°C). Figures 5.64-66 show that the <u>min</u> room temperature most of the time stays between the min and max set point for the room temperature which are respectively 20 and 24°C. Figures 5.64 and 5.67 show that the min supply temperature is dependent on the ambient temperature. But instead of following the original set point line of the BMS the measured supply temperature (top graph in figure 5.67) forms a cloud between the original set point line and 70°C. This is not due to a malfunction in the physical control of the supply temperature as seen when comparing the two top graphs of figure 5.67. The measured supply temperature matches quite well the calculated supply temperature. The curves in figure 5.67 are based on smoothed 15 minutely values in order to obtain the same time stamp on the values on both axis. Figure 5.67 shows that there is not the same number of measurements for the two series of temperatures – the calculated temperature series are especially lacking values at high ambient temperatures.

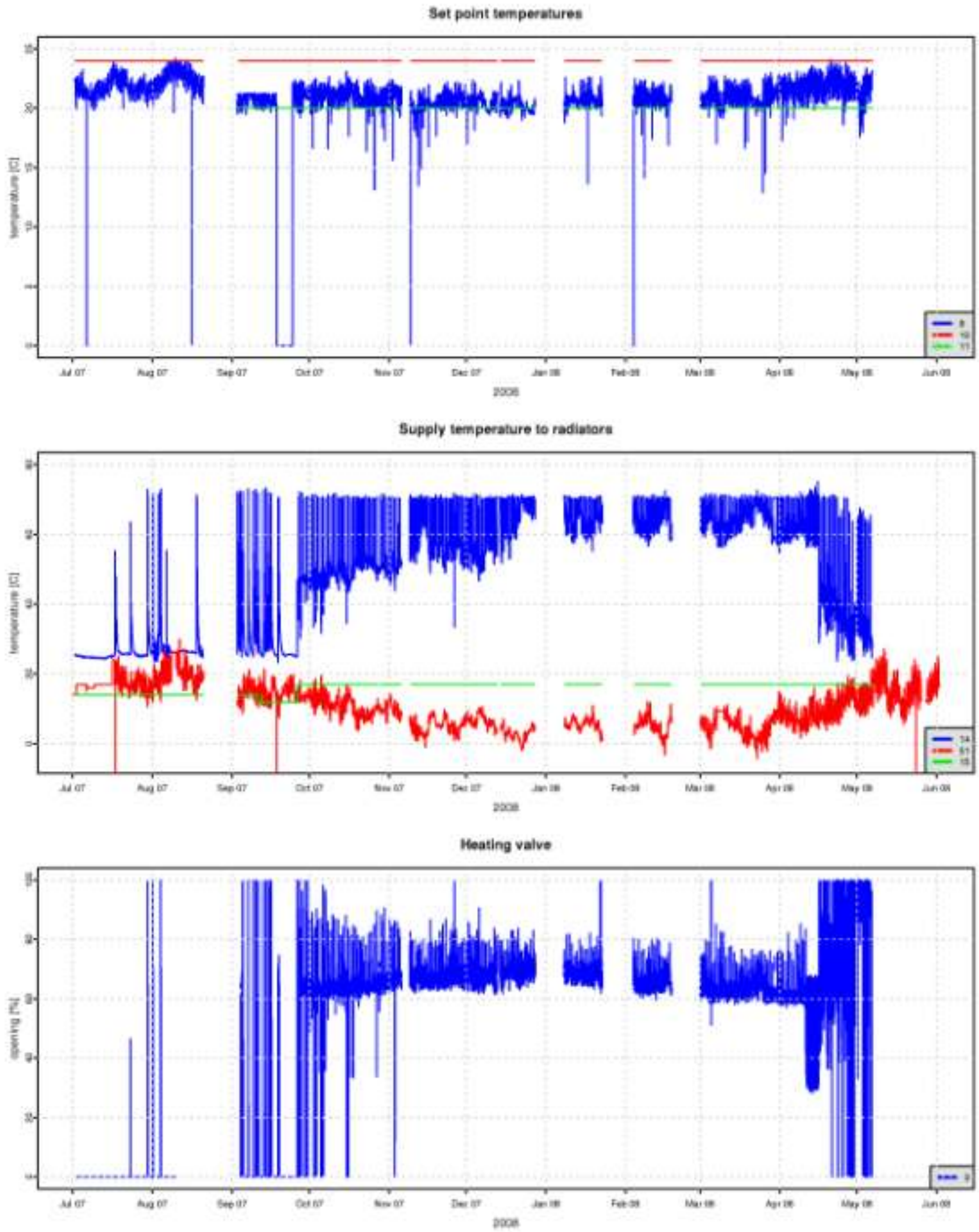


Figure 5.64. Values for the radiator system.

In the bottom graph of figure 5.67 the calculated supply temperature is shown as lines instead of points. In this graph it is seen that there are lines parallel to the original BMS set point line indicating that the BMS set point line has been changed several times during the period – most probably due to complaints. This graph further shows that the calculated supply temperature often jumps from the set point line to 70°C. This is because there is a boost function in the BMS. Each room control contains an ”optimal start program” to insure that the actual room temperature quickly reaches the set point at the start of the working hours. If one ”optimal start program” is active the calculated supply temperature jumps to 70°C,

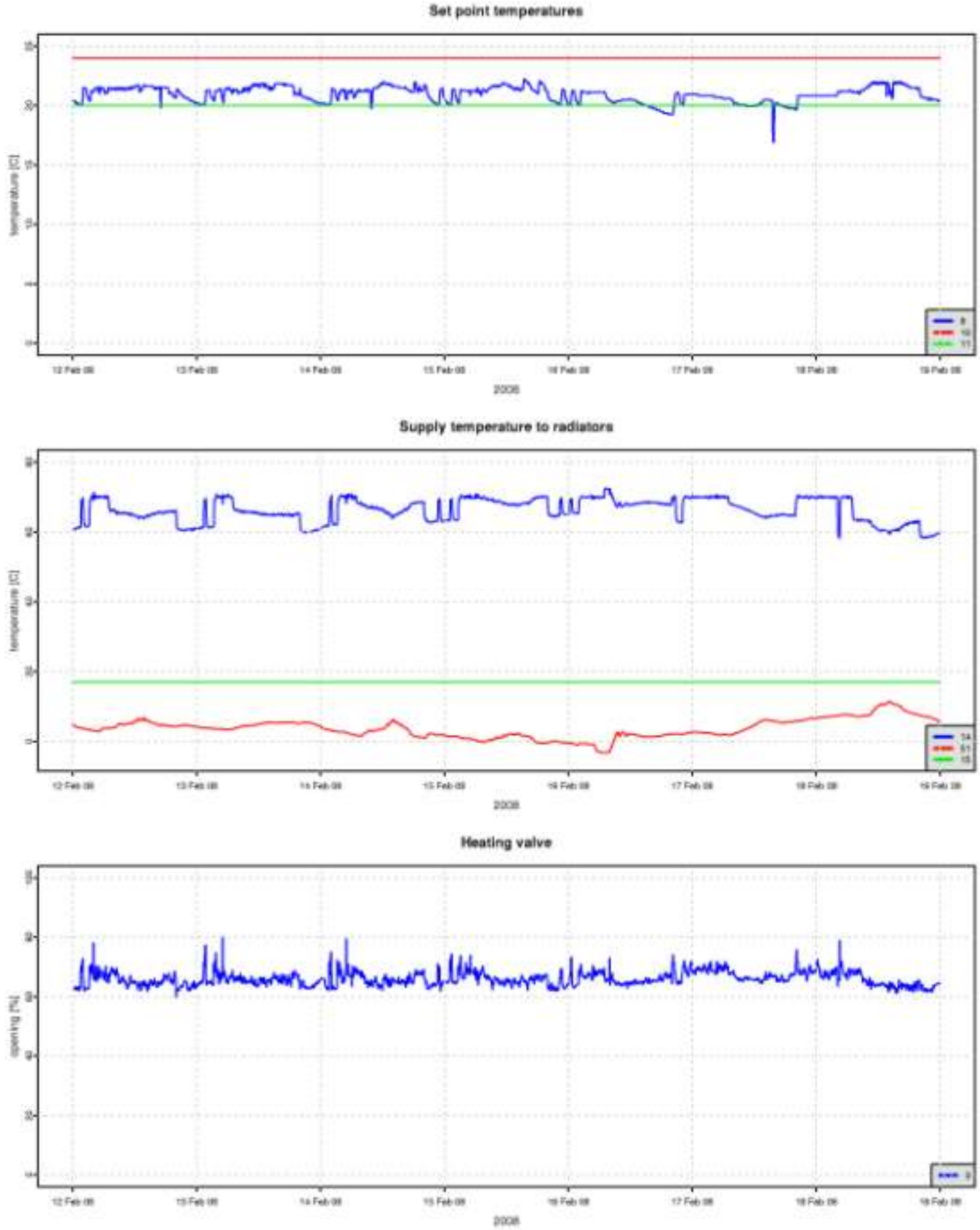


Figure 5.65. Values for the radiator system – winter period.

The jump to 70°C is seen in the mornings in figure 5.66. This further enhances the problem described in section 5.4.2. There is a cooling load during the night so the ventilation system switches to night cooling. This however leads to unnecessary heating of the fresh air in the morning – and as seen in figure 5.66 also a call for heat to the radiators. The call for heat to the radiators can be justified if some rooms are cooled too much during the night cooling. But the top graph of figure 5.66 shows that this is only the fact on May 2-4 while the boost function is also in operation on May 1 and 5-6 where the min room temperature stays above the min set point temperature. And the boost function starts at 0 am on May 5-6. Further it is seen that the boost function is active in the weekend (May 3-4) which is unnecessary and lead to heat losses from the piping which is not valuable, as the building is empty.

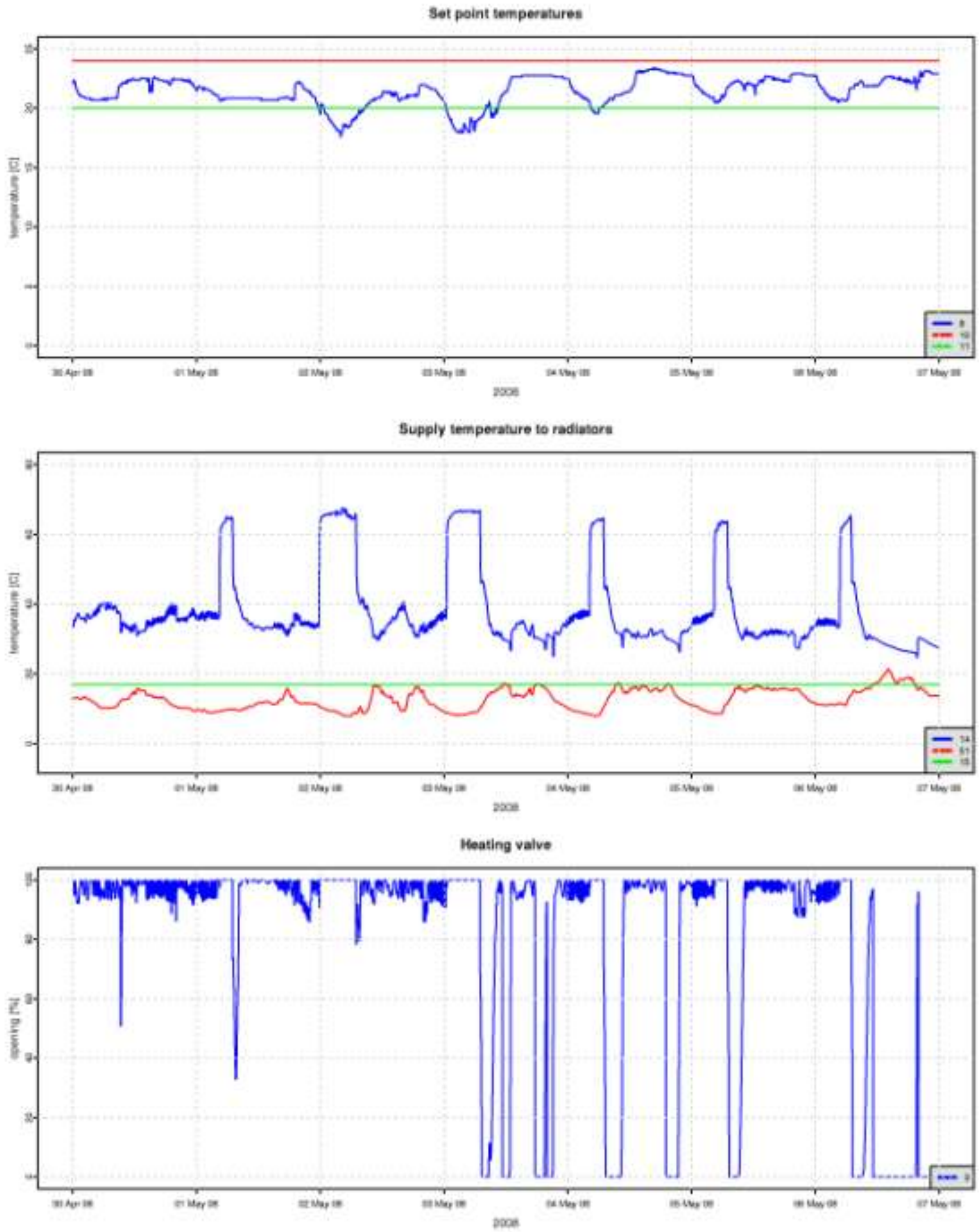
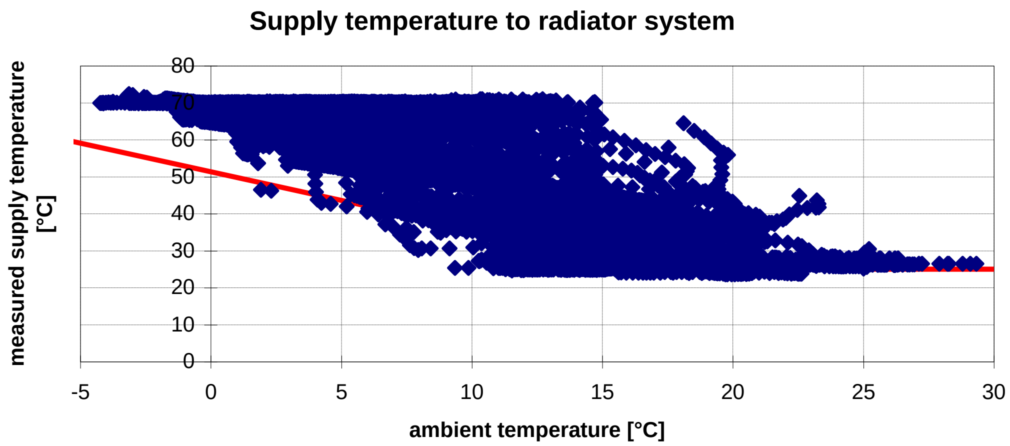
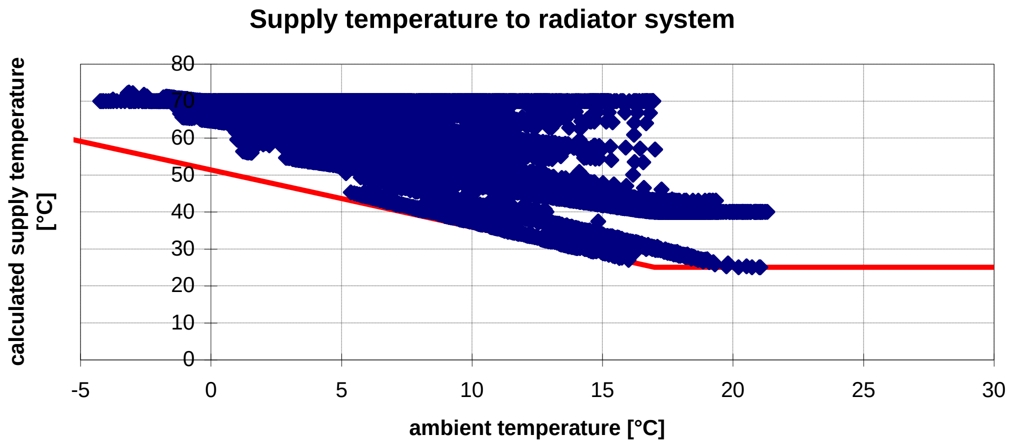


Figure 5.66. Values for the radiator system – spring period.

Figure 5.65 shows rather stable conditions during the winter period. The valve is opened around 65% and the measured supply temperature varies between 60 and 70°C.





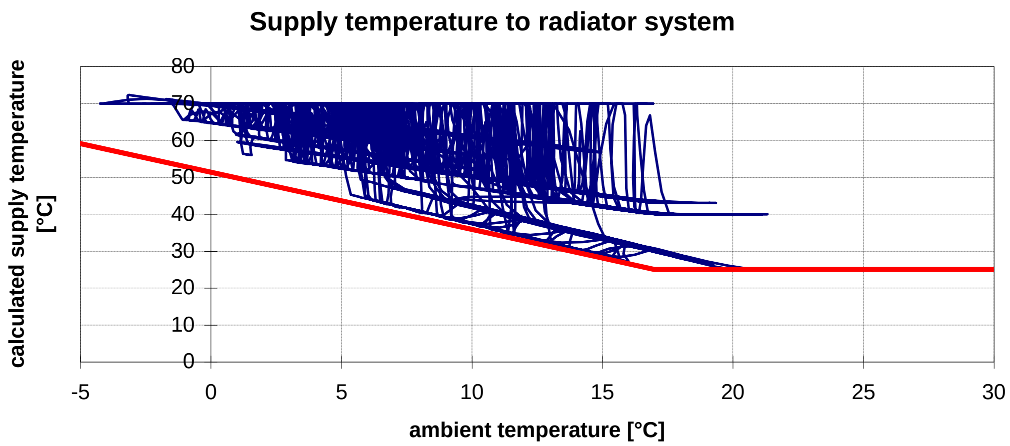


Figure 5.67. Measured and calculated supply temperature to the radiators. The red line is the original set points of the BMS.

The valve is as seen in figure 5.66 fully open most of the time during the spring period. The opening of the valve seems to be more or less correlated with the ambient temperature – ie often the valve closes when the ambient temperature reaches the summer stop. Summer stop

for radiator heating is 18°C (green line in the second graph of figure 5.66). The heating is thus mainly regulated by the supply temperature.
The boost function is active during the spring period. It should be considered if the boost supply temperature should be made ambient temperature dependent as it may save some heating.

Based on the above findings it can be recommended that:

- a better coordination between night cooling and heating in the morning should be developed
- the boost function should not be active during weekends
- it should be considered if the boost supply temperature should be made ambient temperature dependent

5.9. Energy consumption versus ambient temperature

Figure 5.68-70 show the used power from district heating and electricity to installations, cooling system 1 and 2 for the period October 2007-May 2008 (both months incl.). The annual tendency of the power use is not that clear from figure 5.68. In figure 5.71-74 the power use is shown dependent on the ambient temperature.

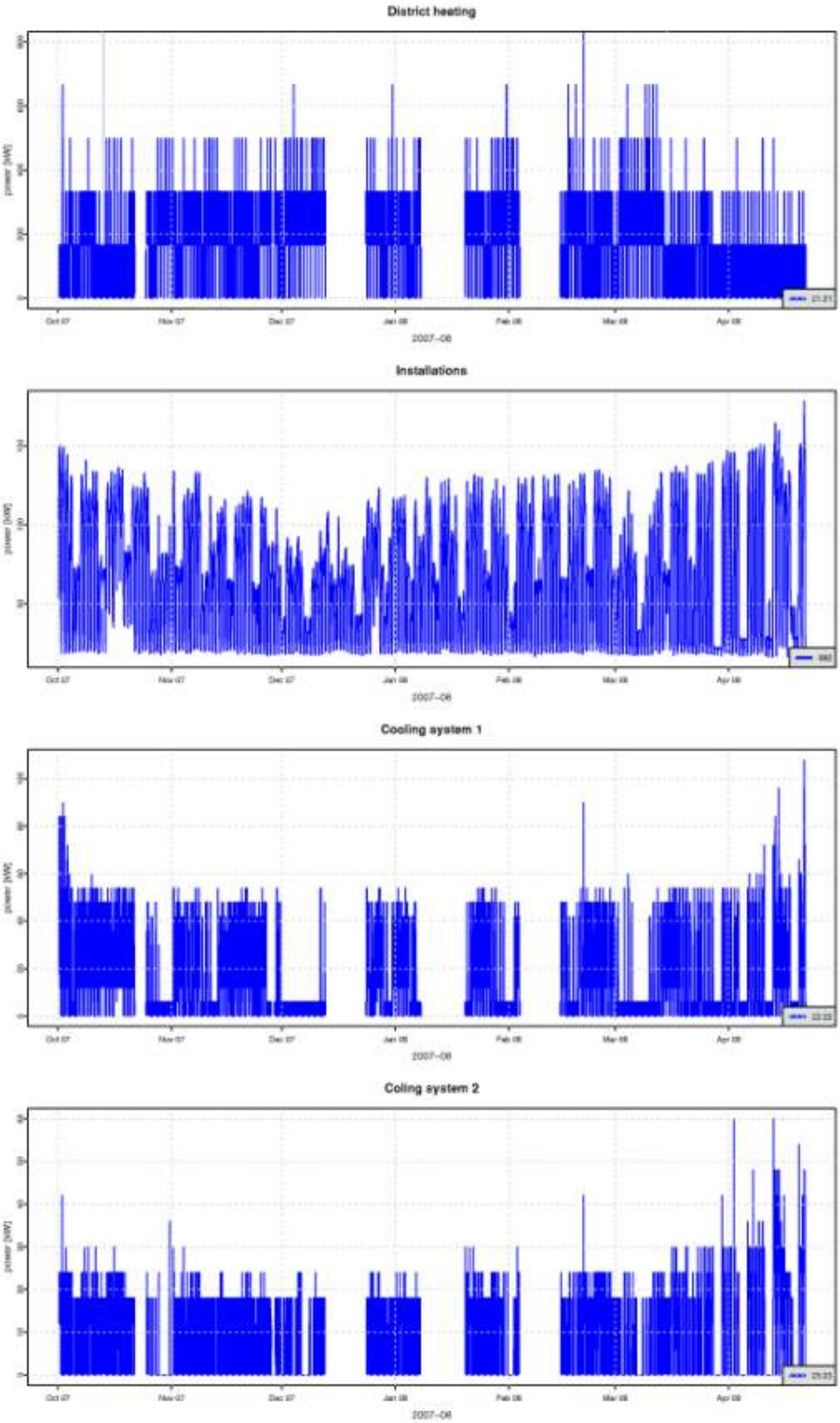
5.9.1. District heating

When plotting the heating demand dependent on the ambient temperature for a building one often obtains a strong dependency on the ambient temperature – a dependency which can be utilized to state something about the UA value + ventilation losses of the building. However, the main part of the values in figure 5.71 is situated below 200 kW (y-axis) and between 0 and 15°C (x-axis). The power decreases above 15°C. Below 13°C there are values above 200 kW and some increase with decreasing ambient temperature. However, below 0°C there is an decreasing tendency. A green line is included in figure 5.71 in order to represent these values. The line crosses the x-axis at 18°C as this is the summer stop of the radiator system. The line crosses the y-axis at 400 kW as this seems to represent the high values between 0 and 5°C. The slope of the line should then represent the UA value inclusive ventilation losses. The slope of the green line is 22 kW/K.

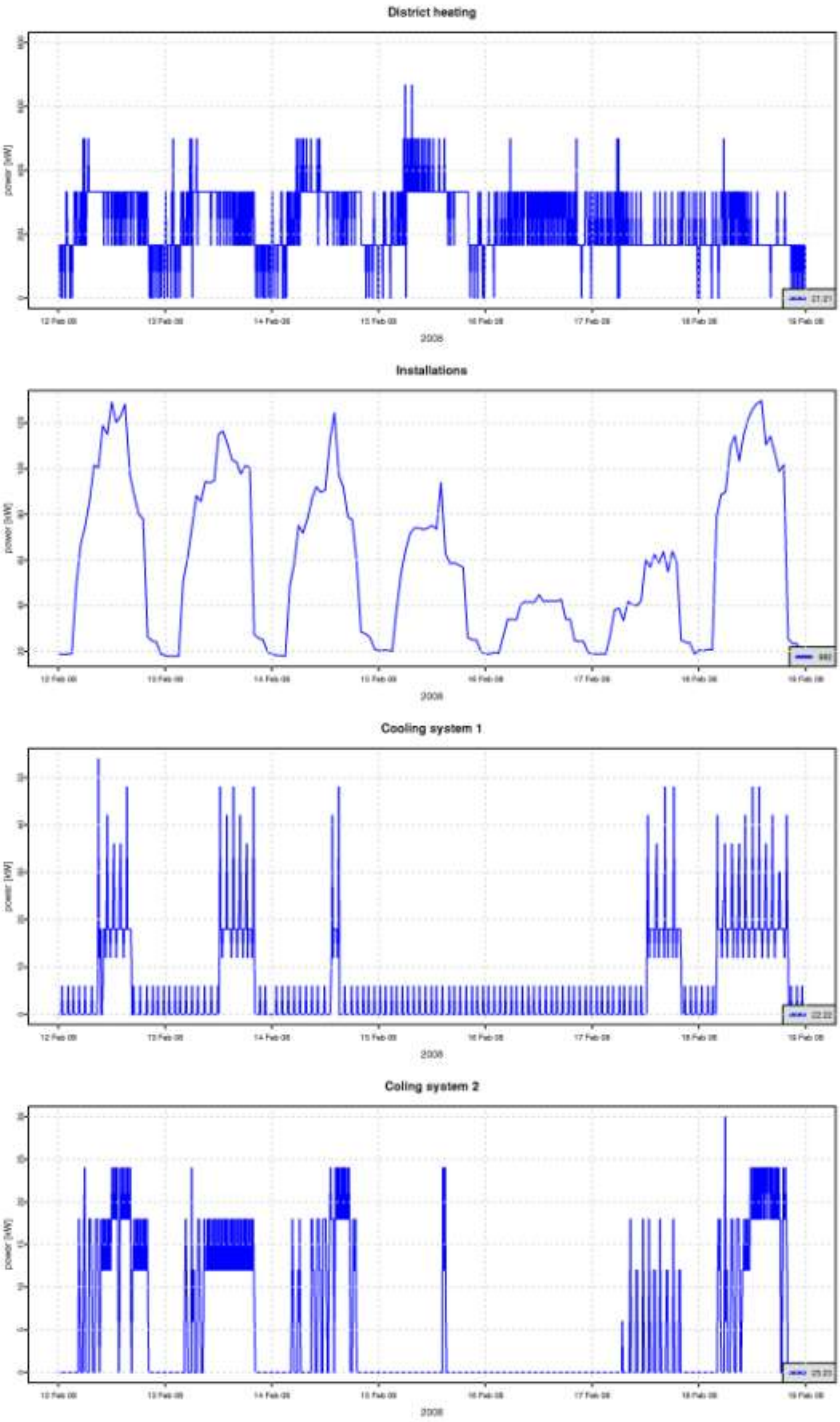
The foot print of the building is 4,946 m². Part of this is in the roof inclined windows (see figure 2.9) which increases the area by a factor 1.9 over the atrium (the area of the atrium is 1,182 m²). The perimeter of the building is 274 m and the height is 19.5 m. This gives a total surface area of the building of 16,300 m².

This leads to a U-value (heat loss coefficient) incl. ventilation losses of 1.35 W/m²K which is close to the assumed U-value of the glazed facades of 1.3-1.5 W/m²K. Main part of the building is glazed, however there is also the floor above the basement, the opaque parts of the facades and the roof with lower U-values which reduce the mean U-value of the building. But when considering the ventilation losses due to a heat recovery factor of 74% and additional infiltration, 1.35 W/m²K seems to be a reasonable value for the mean U-value incl. ventilation losses for the building.

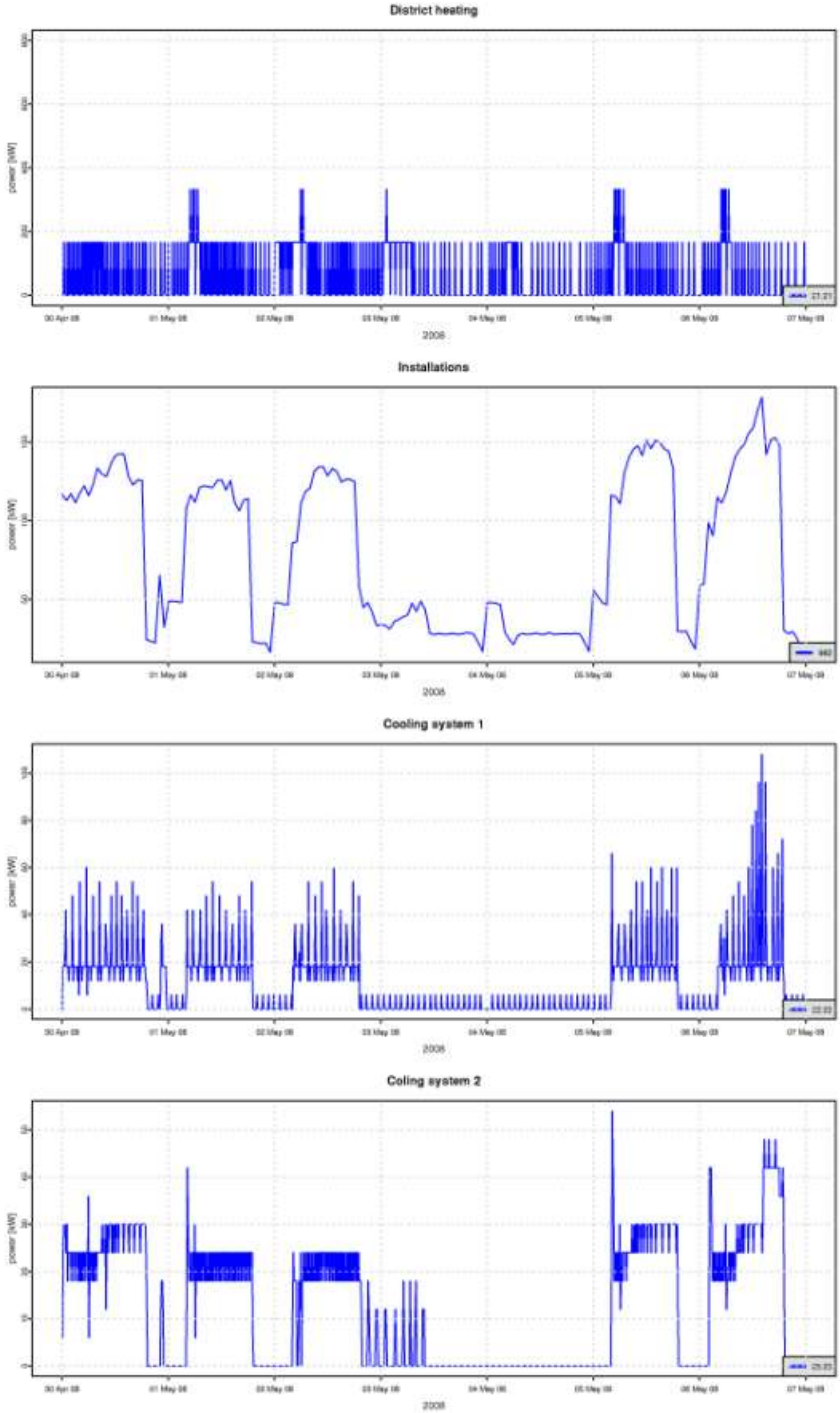
The building is very special in the sense that it has a large heating demand – also at low ambient temperatures. This means that the green curve in figure 5.71 cannot be used as an online evaluation of the heat demand of the building as the values generating this line are very few and it will further be difficult to determine when proper values for the evaluation occur.



Figur 5.68. Power consumptions of the building.



Figur 5.69. Power consumptions of the building – winter period.



Figur 5.70. Power consumptions of the building – spring period.

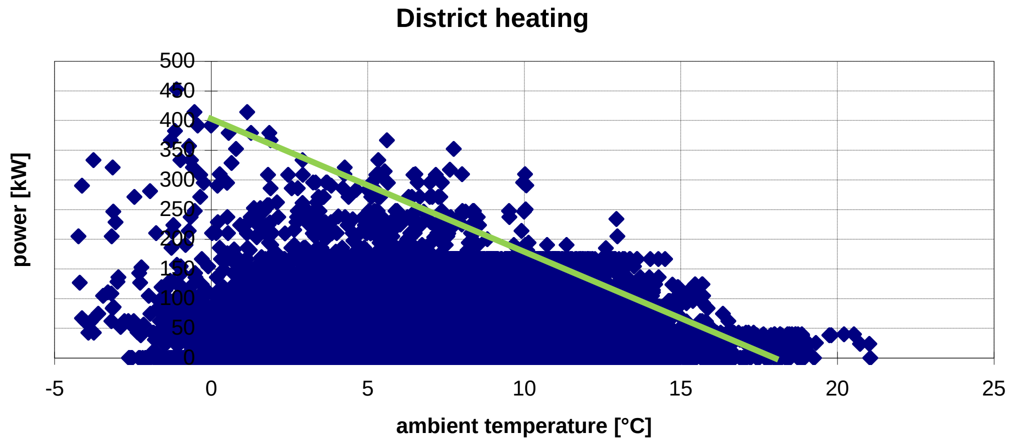


Figure 5.71. The power from district heating dependent on the ambient temperature.

5.9.2. Installations

Figure 5.72 shows the power to the installations as a function of the ambient temperature. The 0 values should be disregarded as the power to the installations was never zero as shown in the second graph in figures 5.68-70. The zeros are wrongly generated by the plotting program.

Figure 5.72 shows as already stated in section 5.3 that the minimum or standby power of the building is around 20 kW – the green box in the second graph of figure 5.72.

During working hours the power consumption is mainly within the red lines in figure 5.72. There is an increasing tendency dependent on the ambient temperature of the max power which is mainly caused by the cooling systems. At 18°C (during working hours) more than 50% of the power to installations is explained by the power to the cooling systems – see figures 5.72-74. At 5°C only 40% of the power to installations is explained by the cooling system and at 0°C less than 2% of the power to installations is for the cooling systems. At 0°C the power of the installations is about 60 kW. This power is used for ventilation, heating (mainly pumps), some lightning, etc. The power is mainly for the ventilation systems. The power consumption of ventilation system 1-4 and 7 is estimated to be in the order of 45 W.

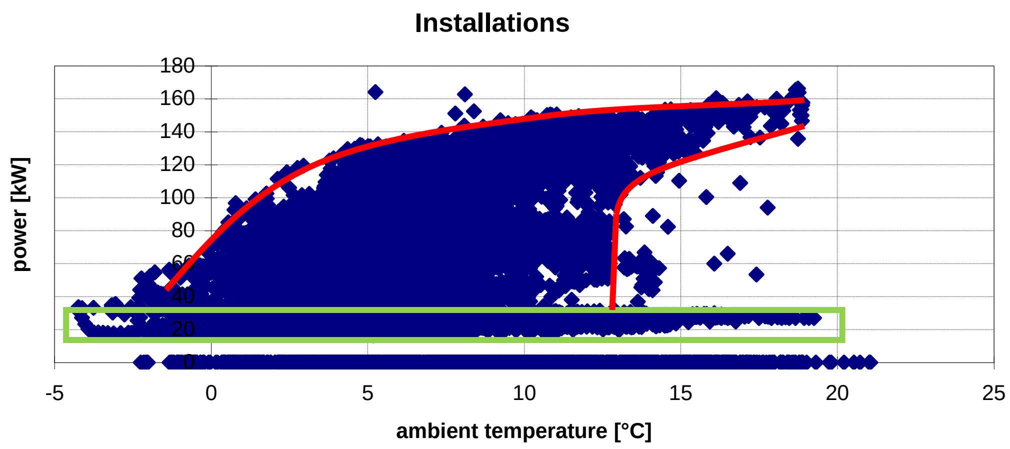


Figure 5.72. The electrical power to the installations dependent on the ambient temperature.

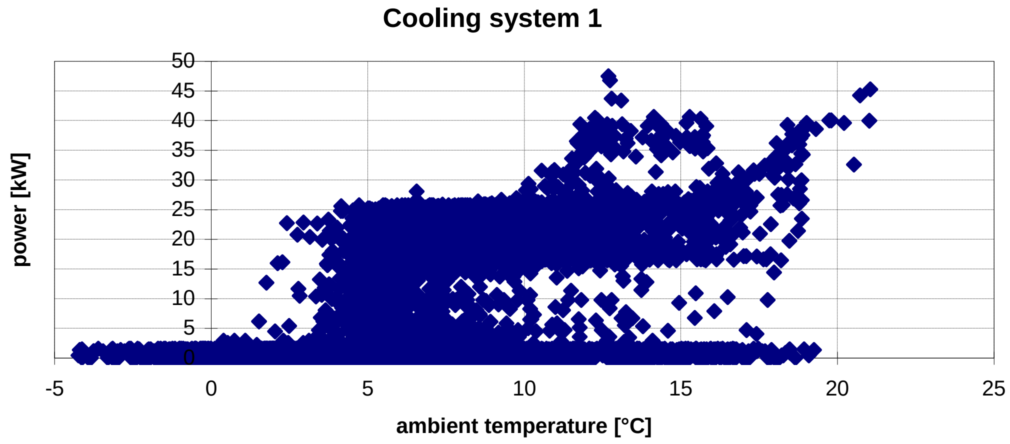


Figure 5.73. The electrical power to cooling system 1 dependent on the ambient temperature.

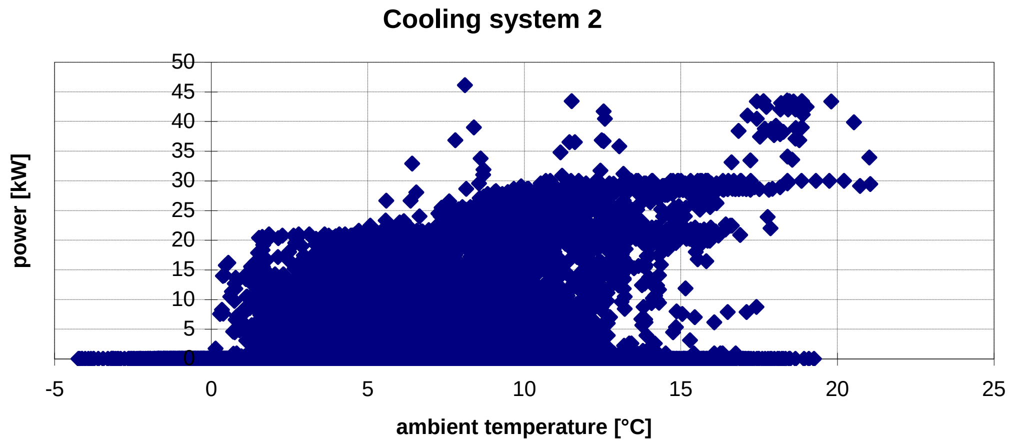


Figure 5.74. The electrical power to cooling system 2 dependent on the ambient temperature.

5.9.3. Cooling systems

Figures 5.73-74 shows the power to the two cooling systems as a function of the ambient temperature. The cooling systems have been dealt with in details in section 5.5, so only few further remarks will be given here.

Cooling system 1 is connected to the ventilation systems for cooling of fresh air to both the CAV and VAV part of the ventilation systems. Figure 5.73 shows that large part of the measured power consumptions is located between 15-27 kW/0-17°C. There are few values in the area 27-50 kW/10-22°C. The power consumption of cooling system 1 has not a clear dependance on the ambient temperature below 22°C. Maybe it is more clearly dependent above 22°C but no data are unfortunately available above 22°C. The low dependency on the ambient temperature is not surprising as cooling system 1 as already mentioned mainly cools fresh air to the VAV part of the ventilation system. The rooms with VAV is mainly rooms situated away from the facades and they further often have a fluctuating cooling load as these often are meeting rooms. The temperature of these rooms is thus not much influenced by the weather.

Figure 5.73 further shows as already mentioned that the system has a small standby power consumption – 0.8 kW. Cooling system 2 does not have such a standby consumption or have a standby consumption which is not measured via the energy meter of KØC2. The standby consumption of cooling 1 should if possible be eliminated.

Cooling system 2 is a bit more influenced by the ambient temperature than cooling system 1 but the main part of the values stays within 0-25 kW and 0-13°C. The low dependency on the ambient temperature may be explained by a large thermal load for the equipment in the building.

The cooling consumption of cooling system 2 stops just before 0°C and does not decrease much until then. This is surprising as this cooling system is equipped with indirect free cooling via the dry coolers on the roof. The free cooling ought to have sufficient capacity below an ambient temperature of around 10°C. The function of the free cooling system should as already mentioned therefore be investigated as much energy may be saved with properly functioning free cooling.

- the standby consumption of cooling system 1 should be reduced
- the function of the free cooling of cooling system 2 should be investigated

5.10. Conclusions

The aim of the work in the present chapter was to investigate if the availability of detailed logged data from a BMS system would enhance the outcome of a traditional inspection of the building and installations. The logged data were already available as instantaneous values on the different BMS screens. On a screen it is however difficult to compare values displayed on different BMS screens and the historic of the values is lost.

The voluminous chapter shows that much interesting and valuable information on the building and installations have been obtained which normally would not be obtainable. The facility management does not have the time to look continuously at the values and to compare the values shown on the BMS screens. Further no time series of data are available. This is even more true during periods without people (including the facility management) in the building.

When looking at time series it is possible to investigate the transient behaviour of the different subsystems and the interactions between the subsystems. In this way faults and inappropriate function of the systems may be detected – in this case: fresh air is often heated first and then cooled, night cooling is not sufficiently utilized, the ventilation systems starts too early and not at the same hour, etc. – all things which are very difficult/impossible to detect when just looking at the instantaneous values on the BMS screen.

Based on the investigations of the logged time series it has been possible to give recommendations on how the indoor climate may be improved and the energy demand may be reduced. These recommendations are highlighted in yellow boxes throughout the chapter. Only an overview of the main suggestions will be given here.

Ventilation systems:

- the volume flow rate of the ventilation systems and the cooling baffles need to be adjusted (reduced) in order to prevent draft and to reduce the energy consumption for the fans

- the running time of the ventilation systems should be not be longer than necessary
- night cooling should be utilized more
- heating followed by cooling of the fresh air should be avoided

It is estimated that a reduction of up to 50% of the electricity demand for ventilation is possible.

Cooling systems:

- modification of the BMS system in order to operate at the highest possible chilled water supply temperature
- reduction of the operation time of the cooling systems
- reduction of pump and fan power
- reduction of standby demand
- better utilization of the free cooling system

It is estimated that a reduction of up to 50% of the electricity demand for cooling is possible.

Heating:

- heating of fresh air when cooling is needed should be avoided
- better control of the supply temperature to the radiators
- better control of heating valves
- allow seasonal variations of the temperature in the atrium

Lack of metering on the subsystems of the heating system makes it difficult to estimate the savings, however, a 20% reduction should be possible.

Work regarding the implementation of the suggested energy saving measures has already begun.

Several of the recommendations are mainly based on the availability of time series of logged data from the BMS. So the traditional inspection has been enhanced – and often been replaced by investigation of time series.

Some lessons have been learned while working with the time series – lessons that are important to consider in future work:

- in the present project the available data from the BMS was just logged as they were – only a few extra sensors were added. The reason for this was to investigate what could be obtained from a traditional BMS as adding sensors is an extra cost upon the cost of the logging. In future projects additional sensors should be specified for obtaining more detailed information in specific areas. Especially energy metering on subsystems is important but also eg additional temperatures sensors which for instance would have made the evaluation of the cooling systems easier.
- in the present project the logged data was transferred by hand. Automatic logging routines should be developed. Routines which also check the quality of the data – eg gives an alarm if data is missing, values are hanging or out of range, etc – should be developed.

- it is very time consuming to investigate thousands of time series by eye and also very expensive as the work should be done by experts. Routines to automatically check the main parameters should be developed but also routines which in a condensed and easy readable form present the actual condition of the building and installations for the facility management so that the facility management may react appropriately. Cumulated frequency curves are such a tool but need further development.
- and by the end of the day multiparameter controllers which automatically are able to optimize the indoor climate while minimizing the energy demand should be developed. This will be discussed in the following chapter.

The results from the visual inspection relate specifically to the investigated building and cannot directly be transferred to other buildings as the installations and control may differ considerably from the here investigated building. However, it is judge that the result from the project may act as a source inspiration for finding fault and inappropriate functions in other buildings which may lead to considerably energy savings. But the energy saving potential will be increased if time series from the BMS are logged.

6. Multiparameter controllers

Recently, combined improvements in data mining and computer performance have allowed new types of investigations on large data sets, creating new perspectives to enhance the control strategy of HVAC systems when many hundreds of control signals are available. Those signals can report the states of various parameters of a building: air temperature in a room, solar radiation, energy consumption, etc (see chapter 5). However, to optimize the overall control strategy of such a system, specific signals and statistics summarizing the relevant information in the data must be generated. These signals and statistics are likely to reveal the underlying structure in the data, as well as extreme behaviors of some parameters. The spurious information is then discarded. The present chapter introduces the workflow of a classic statistical study and gives an example of the use of a data mining to investigate the types of multiparameter sensors which can be generated based on the logged values from the Building Management System (BMS).

6.1. Data description

The first step of a statistical study is to assess the quality of the available data. It consists in investigating on each of the following dimensions:

- Accessibility: the extent to which data is available, or easily and quickly retrievable (see Appendix 6),
- Completeness: the extent to which the data are not missing,
- Interpretability: the extent to which the data are in appropriate units,
- Free-of-error: the extent to which data are correct and reliable.

The most difficult task is to identify erroneous measurements (outliers) in the data and it must be handle with special care because the quality of the results of a statistical analysis can be strongly affected by such measurements. It is particularly true when those outliers are extreme because most of the statistical methods are very sensitive to extreme values.

Assessing the quality of a data set often gives an good idea on which data could be useful for the analysis and which type of analysis should be performed. The less reliable the measurements are, the more robust the method used should be.

6.1.1. Data overview

As reported in chapter 3, the data consist of 1050 time series collected from three different sources:

- 975 time series from the BMS system, with a temporal resolution of one measurement every 5 minutes (but for time series 20 and 25 whose temporal resolution was 10 minutes and time series 967, 968, 969, 970 and 971 whose temporal resolution was 1 hour),
- 7 times series from DONG Energy, with a temporal resolution of one measurement every 1 hour,

- 68 extra times series specifically logged for the purpose of the Multiparameter controller project (see chapter 4), with a temporal resolution of one measurement every 15 minutes.

Logging took place from July 1, 2007 to August 31, 2008. However, the time series are heterogeneous with respect to the period they cover and missing measurements. Figure 6.1 illustrates the problem of missing measurements for time series 51 showing the ambient temperature measured by the BMS system. The series 51 is partially spoiled by a few sequences of missing measurements, constant measurements (in July 2007) and outliers (the three spikes). It turns out that there are not so many sequences of missing measurements. However, these sequences are quite long, from 7 to 15 days, and from a statistical perspective it would not be very relevant to fill in those gaps in the data.

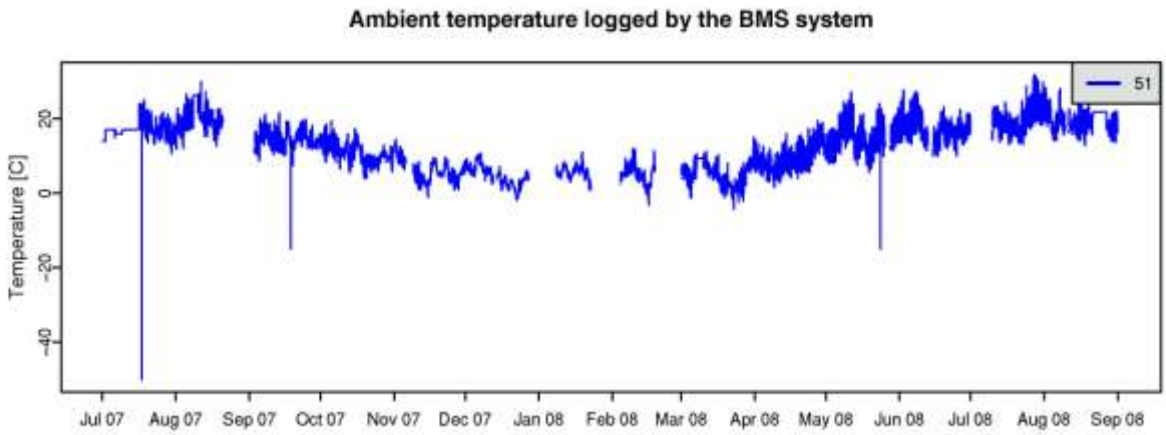


Figure 6.1. The ambient temperature logged by the BMS system.

Figure 6.2 illustrates the problem of measurements which do not cover the same time period. Time series 264, logged by the BMS system, and time series 1000, specifically logged for the purpose of this project, show the fluctuations of the air temperature in room 230. Although time series 1000 was not meant to cover the entire logging period (July 2007 – August 2008), it could have been useful if it did. One could have use time series 1000 to fit a model (explain time series 264 with respect to time series 1000) and fill in the sequences of missing measurements in time series 264.

Those issues are even more relevant in the Multiparameter controller project since the study focuses on the energy consumption and the indoor climate of a building mainly occupied during working hours/days. In an ideal case with no missing measurement, one could try to compare the behaviour of the building during the working period and its behaviour during holidays (when the occupancy rate is significantly different).

The information provided for the three sources of data confirmed that the logger clocks were synchronized on the Central European Time (CET), one hour ahead of the Coordinated Universal Time (UTC). However, the BMS and DONG Energy loggers were automatically adjusted for Day Saving Time (DST) whereas the loggers used for the specific measurements were not. The loggers were synchronized on the time of the connected computer when they were launched. In 2008, summertime started on March 30, but loggers were launched on March 6 and dates from March 30 to June 25, when loggers were re-launched, should therefore be adjusted manually. Wintertime began on October 26 and logging ended when the loggers were removed from the building on October 28. The dates from October 26 to October 28 should thus be adjusted to wintertime, since the computer was on summertime when launched again. As a summary, the following corrections were applied on all 68 time series for the specific measurements:

- positive time-stamp shift of 1 hour from March 30 to June 25, 2008,
- negative time-stamp shifts of 1 hour from October 26 to October 28, 2008.

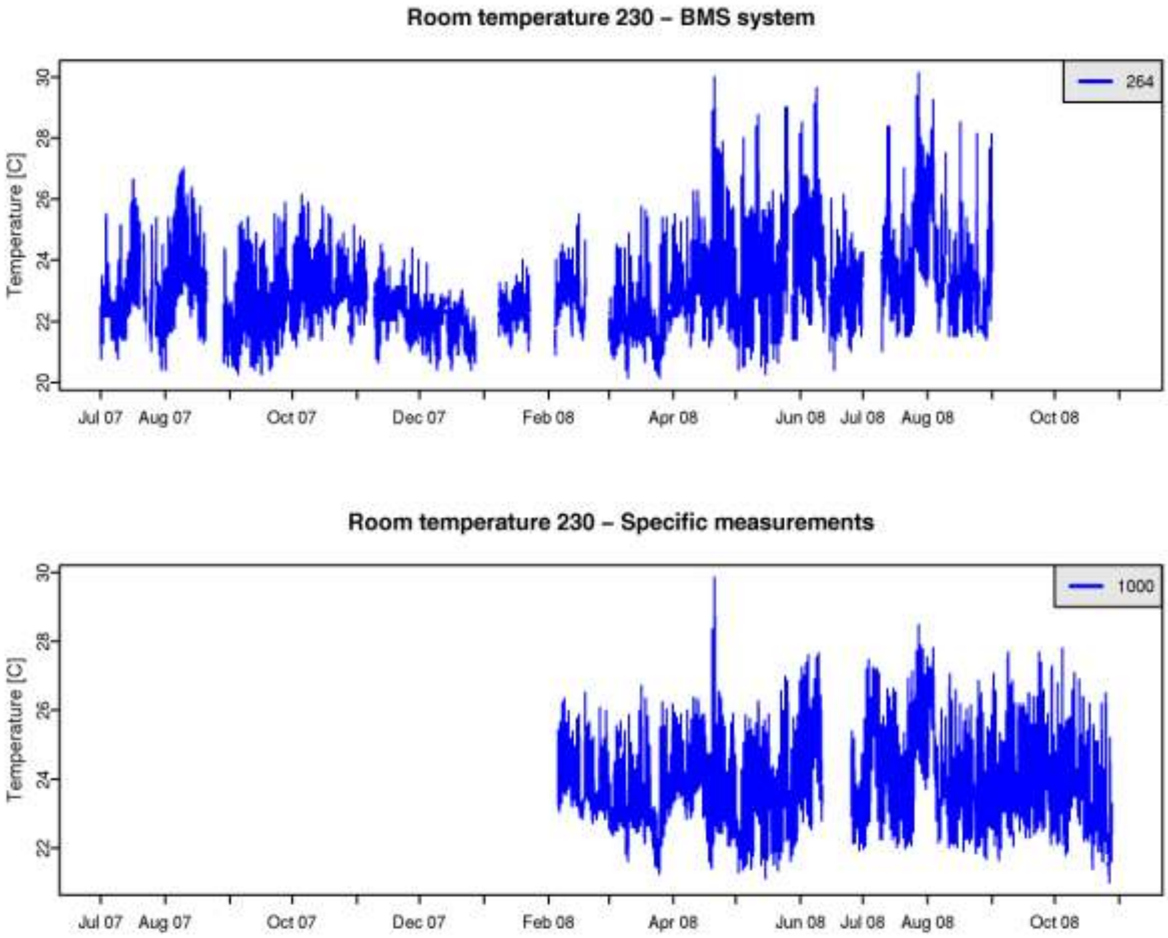


Figure 6.2. The air temperature in room 230 logged by two different systems.

6.1.2. Missing measurements

6.1.2.1. BMS measurements

Almost all the series from the BMS system exhibits the same gaps in the data. Figure 6.3 illustrates this on time series 474 (air temperature in room 332), 33 (CO_2 level in exhaust) and 50 (air temperature from the building before it reaches the heat exchanger). On all three series, relatively long gaps (7-14 days) can be observed in August 2007, December 2007, January-February 2008 and July 2008. Time periods over which data are missing overlap with national holidays (Christmas, Winter holidays, Easter and Summer holidays). Logging of data was performed automatically but the transfer of data had to be done manually. For the purposes of future projects, it is recommended to evaluate the possibility in setting up an automatic procedure which could prevent these problems.

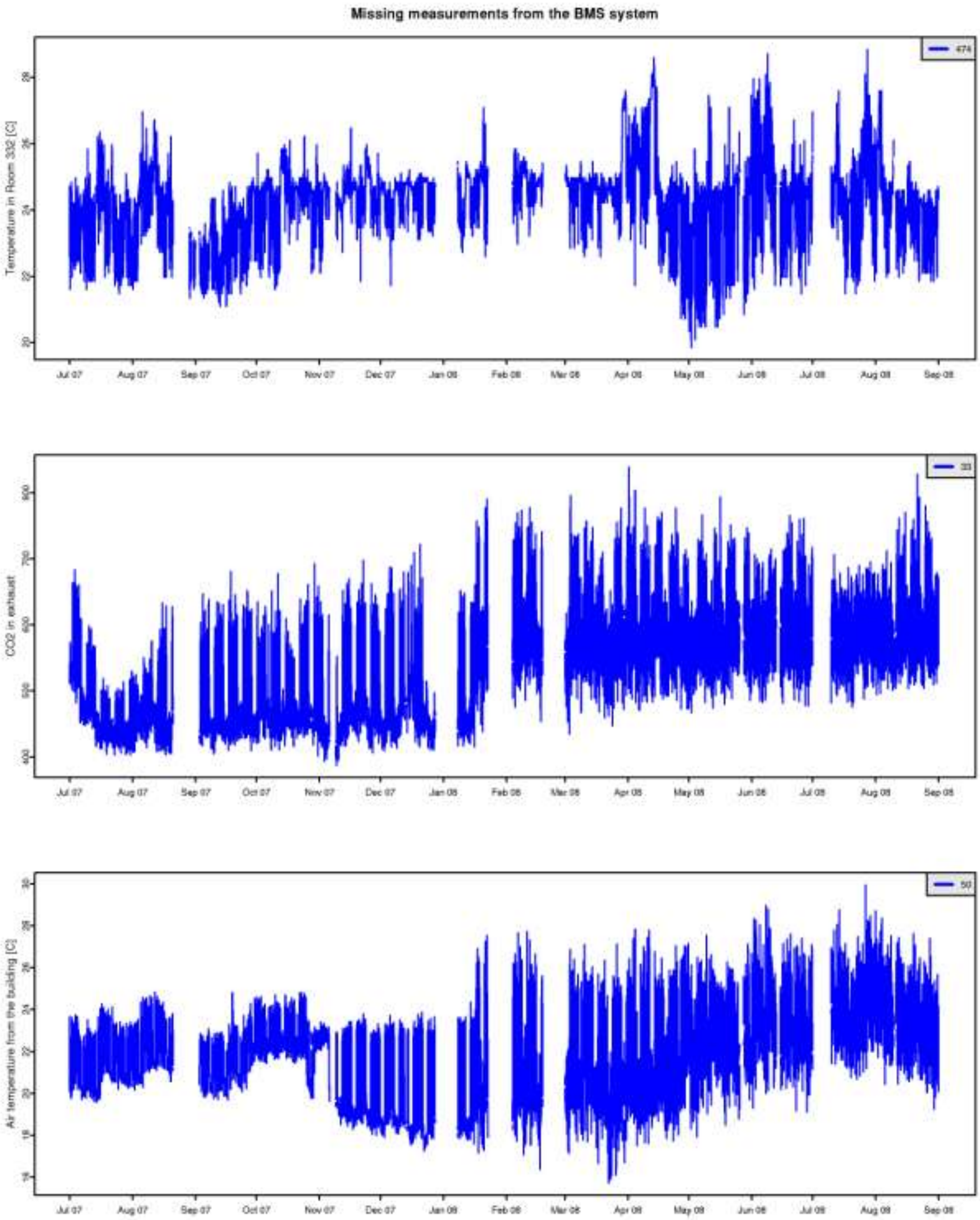


Figure 6.3. Missing measurements in the data from the BMS system.

6.1.2.2. Specific measurements

Specific measurements regarding the air temperature, relative humidity, solar radiation and the CO_2 level was carried out at several locations. As shown on figure 6.4, those measurements also exhibit gaps in their records. It can be a gap of three months like for the air temperature in room 322 or even larger gaps in some other series.

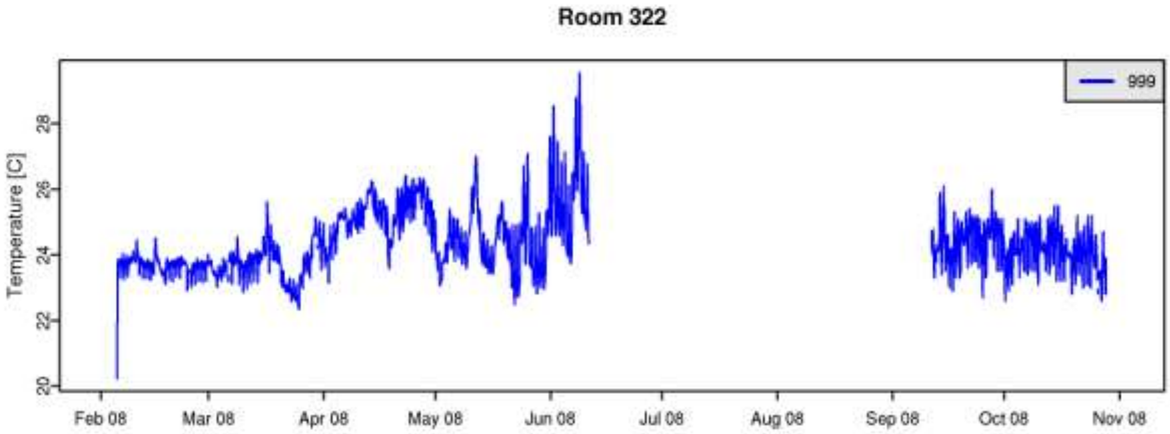


Figure 6.4. An example of the specific temperature measurements.

6.1.3. Detection of errors in data

Searching for potential outliers and more generally speaking assessing the quality of a data set is a tedious and difficult task. A broad definition of an outlier which is often given is "an observation that is numerically distant from the rest of the data". Numerous types of outlier related problems have been addressed in the literature but a brief visual inspection of the data often provides a clear insight on the types and occurrences of outliers. In the present project, we restricted the scope of our investigation to the outliers which are caused by faulty measurements (or logging errors). Although, most of these faulty measurements were found to occur when loggers started or re-started after a period of time over which they were not functioning, they also occurred randomly.

Investigating for outliers and calibrating a method for each of the 1050 time series would have been too time-consuming. A visual inspection of the data and building revealed, however, that there was a very small percentage of outliers, with respect to the definition given previously. Therefore, a simple but robust 3-step procedure was developed. The first step of the procedure consisted in searching for and removing sequences of constant measurements of significant duration in all the time series of air temperature. The second step consisted in identifying sudden and/or temporary drops, jumps or shifts of significant amplitude in the temperature logged in all offices. At last, the third step of the procedure, when needed, consisted in removing the remaining "obvious" outliers by hand.

For the first two steps, the difficulty of the task is to differentiate the faulty measurements (data adding spurious variability) from physical phenomena caused by specific local conditions (relevant variability we want to keep). For instance, it is very much likely that a sudden drop in the logged temperature in a room could be caused by the start of the cooling system/baffle, located just above the sensor (see chapter 5). The cold air flow coming out of the cooling baffle is then directly hitting the sensor. Another explanation could be a malfunction of the system.

6.1.4. Sensor accuracy

This subsection introduces the problem of automatic measurements of physical data which often contain sequences of constant readings. They are likely to be caused by faulty measurements or a temporary lack of accuracy of the sensors and hence must be removed. Errors may cause some data loggers to keep recording the same measurement (temperature, for instance) while in fact they are not working.

The study was carried out on a panel of 63 measured room temperatures (all the rooms located on the first and second floor of the building). For these rooms, we computed the number of sequences of constant measurements longer than 1, 5, 10, 15 and 20 hours, based on the original measurements. A sequence of constant measurements for one hour means that there are 12 constant values read in a row (at a temporal resolution of 5 minutes). Table 6.1 gives a summary of this investigation on the accuracy of the BMS sensors. It was not possible to correlate these information neither with the relative location of the rooms in the building (by the atrium (Atri), by the external facade (Ext) of the building or inner room (Inn)), nor with the ventilation system (VEN1, VEN2, VEN3), nor with the orientation of the windows (North, East, etc), nor with the area of the rooms, nor with the solar radiation). However, the results are surprisingly significant to wonder whether the sensors (whose precision is 2 digits) are able to accurately capture the air temperature fluctuations in real time. Figure 6.5 illustrates this problem for room 209.

The coarse scale of the plot over the entire logging period does not allow to observe anything but when one looks at the same measurements over a shorter period (bottom graph in figure 6.5), one can notice the strange temperature fluctuations logged with many sequences of constant readings. This pattern was identified for all the investigated rooms. The same study was done for the specific measurements whose temporal resolution was 15 minutes. A sequence of constant measurements for one hour means there are 4 constant values read in a row. Table 6.2 summarizes the results for the rooms located on the first and second floors. These results tend to indicate that the sensors used for the specific measurements can better capture the short term fluctuations of the air temperature (see also section 5.2).

From a statistical perspective, sequences of constant measurements equal or longer than 5 hours are not acceptable. However, removing those measurements would have resulted in removing more than 30% of the time points originally available from the BMS systems. Therefore, we decided to remove the sequences longer than 10h (about 10% of initial time points removed).

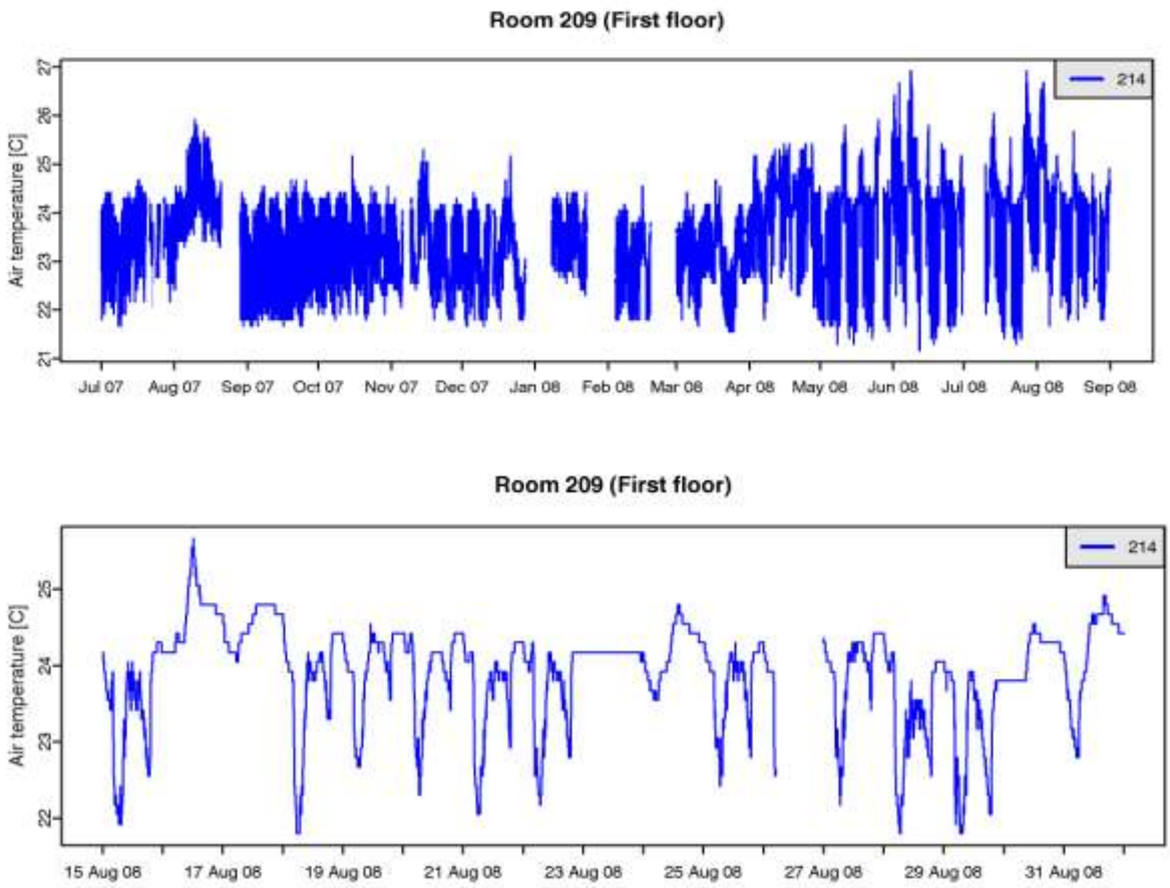


Figure 6.5. Time series 214 exhibits many sequences of constant measurements.

Series	Rooms	Ventilation system	Facade	Window orientation	>1h	>5h	>10h	>15h	>20h
169	201	VEN1	Ext	East	1993	130	11	0	0
174	202	VEN1	Atri	West	1691	95	7	1	1
179	203	VEN1	Inn	-	1813	171	25	3	2
184	204	VEN1	Ext	North	963	2	0	0	0
189	205	VEN1	Ext	North	836	10	0	0	0
194	206	VEN1	Ext	North	1006	11	0	0	0
199	207	VEN1	Ext	North	913	10	0	0	0
204	231	VEN1	Ext	North-East	891	5	0	0	0
209	208	VEN2	Ext	East	1398	59	6	1	1
214	209	VEN2	Atri	West	1191	61	8	1	1
219	210	VEN2	Inn	-	1723	95	12	1	1
224	211	VEN2	Ext	East	1257	69	14	1	0
229	212	VEN2	Ext	South-East	1446	34	4	0	0
234	213	VEN2	Ext	South	2060	94	7	1	0
239	214	VEN2	Ext	West	1875	110	10	2	1
244	215	VEN2	Inn	-	2000	111	12	1	0
249	216	VEN2	Inn	-	1257	64	7	0	0
254	217	VEN2	Atri	North	2098	152	20	3	1
259	218	VEN2	Inn	-	1935	119	9	1	1
264	230	VEN2	Ext	West	1180	30	0	0	0

269	219	VEN3	Inn	-	675	20	2	0	0
274	220	VEN3	Atri	East	1259	111	21	5	1
279	221	VEN3	Ext	West	1238	21	2	0	0
284	222	VEN3	Ext	West	1547	40	4	1	0
289	223	VEN3	Inn	-	1495	51	3	2	0
294	224	VEN3	Ext	West	714	14	2	0	0
299	225	VEN3	Atri	EAST	1658	50	4	0	0
304	226	VEN3	Atri	East	1605	116	23	6	2
309	227	VEN3	Ext	North	1149	33	2	1	0
314	228	VEN3	Ext	North	1526	49	5	0	0
319	301	VEN1	Ext	East	1441	125	13	2	0
324	302	VEN1	Atri	West	1303	147	17	4	2
329	303	VEN1	Ext	East	1440	36	4	1	1
334	304	VEN1	Ext	East	1400	105	8	1	1
339	305	VEN1	Inn	-	1691	146	24	4	2
344	306	VEN1	Atri	West	1629	187	33	3	2
349	307	VEN1	Ext	North	1061	17	2	1	0
354	308	VEN1	Ext	North	1508	69	16	4	0
359	309	VEN1	Ext	North-East	1163	13	0	0	0
364	310	VEN1	Ext	East	1440	131	30	10	5
369	311	VEN2	Ext	East	1891	122	17	0	0
374	312	VEN2	Atri	West	1925	121	5	1	1
379	313	VEN2	Inn	-	1086	61	8	1	0
384	314	VEN2	Inn	-	1278	102	11	0	0
389	315	VEN2	Ext	East	1321	47	4	1	0
394	316	VEN2	Ext	South-East	1466	36	1	0	0
399	317	VEN2	Ext	South-West	1701	46	6	1	0
404	318	VEN2	Atri	North	1600	78	3	1	1
409	319	VEN2	Inn	-	1649	106	5	2	0
414	320	VEN2	Inn	-	1338	69	2	0	0
419	321	VEN2	Ext	West	1078	53	1	0	0
424	322	VEN3	Atri	East	1759	88	12	4	2
429	323	VEN3	Ext	West	1221	41	6	0	0
434	324	VEN3	Ext	West	1238	31	4	0	0
439	325	VEN3	Inn	-	1412	115	27	11	6
444	326	VEN3	Inn	-	1646	115	32	11	2
449	327	VEN3	Inn	-	1444	101	16	9	6
454	328	VEN3	Atri	East	1627	143	25	10	2
459	329	VEN3	Inn	-	1497	70	7	2	0
464	330	VEN3	Inn	-	1739	121	18	3	1
469	331	VEN3	Inn	-	1533	41	2	0	0
474	332	VEN3	Inn	-	1530	86	11	2	0
479	333	VEN3	Inn	-	1504	73	7	2	0
51					15	12	9	8	8

Table 6.1. Summary of the number of sequences of constant measurements for the time series of room temperature (Floor 1 and 2) from the BMS system.

Series	Room	>1h	>5h	>10h	>15h	>20h
989	208	528	11	1	0	
991	324	145	0	0	0	0
993	214	267	3	0	0	0
994	212/213	453	12	2	0	0
995	302	357	3	0	0	0
996	313	461	6	0	0	0
999	322	582	16	1	0	0
1000	230	245	2	0	0	0
1004	316	120	0	0	0	0

Table 6.2. Summary of the number of sequences of constant measurements for the time series of room temperature (Floor 1 and 2) – specific measurements.

To make sure that the problem of these sequences of constant measurements do not depend on the BMS system computer (meaning a generalized problem on the entire system causing a loss of connectivity in between the computer and all the loggers at the same time) but rather on each sensor individually (meaning that sensors could not read accurately very small fluctuations of the temperature), we computed the distribution of the number of sensors affected by that problem for a minimum duration of 5 hours. Figure 6.6 shows the results for the entire logging period, from July 2007 to August 2008. The problem seems to affect a lot of sensors whatever the period of the year, reaching a peak of 37 (out of 63) sensors in August 2008. To better understand what happened, the scale of the plot was refined. Results for one month are shown on figures 6.7, 6.8 and 6.9. In July 2007 (see figure 6.7), one can observe a clear periodicity with high peaks during the week end (July 2, 2007 was a Monday). The same periodicity is observed in November of the same year (see figure 6.8), along with more problems during the week days (November 12, 2007 was a Monday). Again, it is possible to observe the same pattern in April 2008 (see figure 6.9). In the same way, the time when the problem occurs was investigated: does it occur more at night than at day? Figure 6.10 shows that sensors are almost exclusively affected by that problem during the night in the week days and that the problem is general in the week end. A naive assumption is that the air temperature varies more slowly in the week end and at night, when offices are not occupied. However, when a higher frequency (smaller duration for the sequence of constant measurements) is considered, the problems is extended to many more sensors during the week days, both at night and day (see figure 6.11). The number of sensors affected goes over 20 at day and over 50 at night.

These latter results raise the question of the reliability of the BMS sensors. It seems that they are relatively accurate to capture the mean air temperature but poorly capture its short term fluctuations. This may partially explain the difficulties encountered when applying statistical methods to model the complex variability of the energy consumption and the indoor climate of the building.

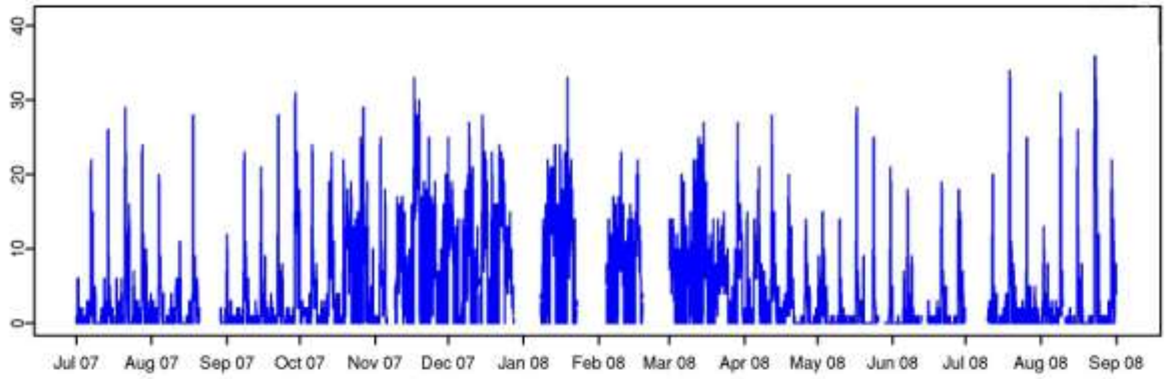


Figure 6.6. Number of sensors reading constant temperature (for a minimum duration of 5 hours) from July 2007 to August 2008.

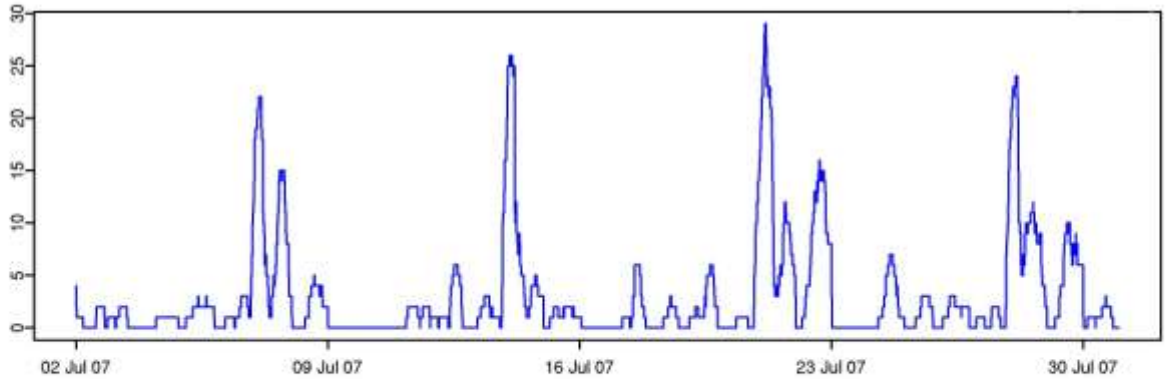


Figure 6.7. Number of sensors reading constant temperature (for a minimum duration of 5 hours) in July 2007.

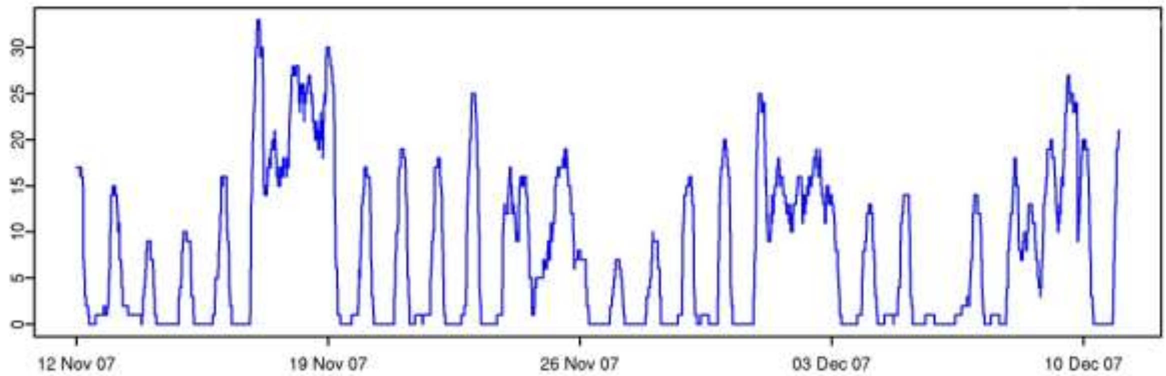


Figure 6.8. Number of sensors reading constant temperature (for a minimum duration of 5 hours) in November 2007.

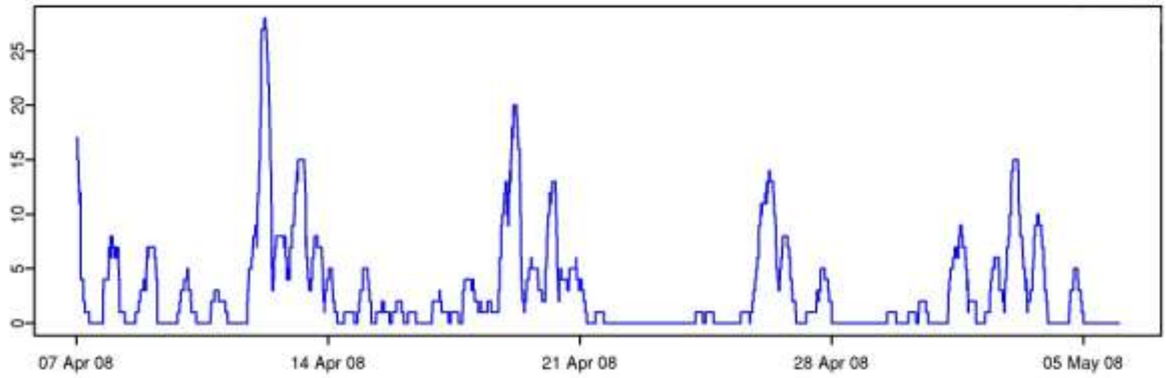


Figure 6.9. Number of sensors reading constant temperature (for a minimum duration of 5 hours) in April 2008.

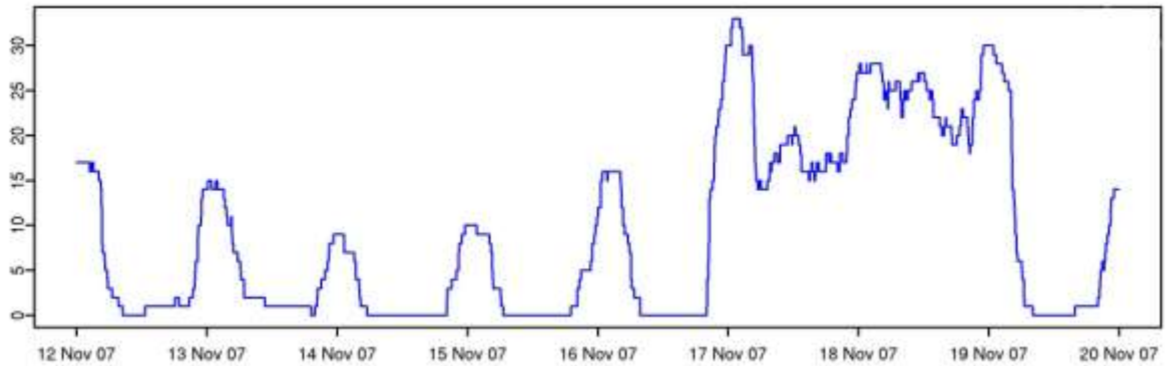


Figure 6.10. Number of sensors reading constant temperature (for a minimum duration of 5 hours) - One week in November 2007.

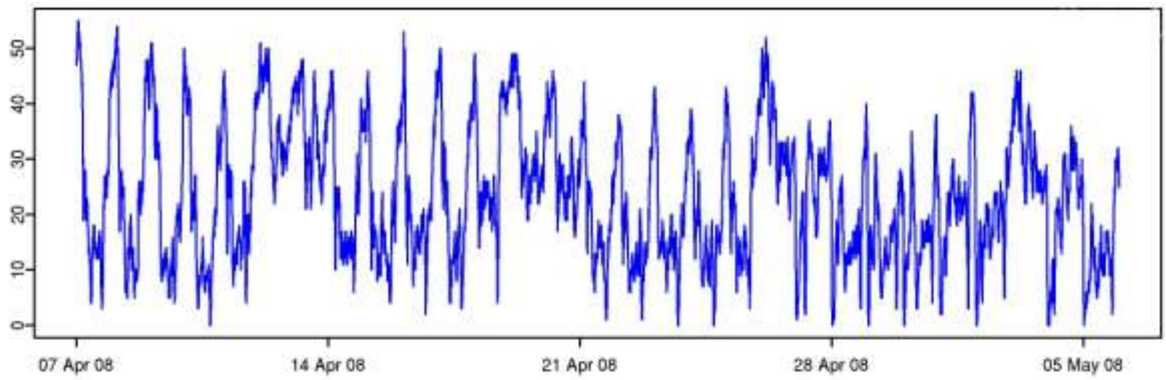


Figure 6.11. Number of sensors reading constant temperature (for a minimum duration of 1 hours) in April 2008.

6.1.5. Outliers

This step of the procedure was only applied the to time series of air temperature and ambient temperature. The classical approach to deal with "serial" outliers (outliers in time series analysis) is to fit a model to a time series and identify outliers based on the residuals analysis. It is called the diagnostic approach. Outliers can be:

- additive which corresponds to an external error or exogenous change of the time series at a particular time point,
- level shifted which corresponds to a modification of the local mean or level of the process starting from a specific point and continuing until the end of the sample.

In general, "serial" outliers should be identified by examining the original, unmodified time series. However, if the series has a significant long-term trend, seasonalities, diurnalities (different behaviour at day and night), it may be appropriate to remove them prior to checking for outliers. Nevertheless, removing those features was a very tricky operation for many reasons:

- missing measurements spanning over several days during key periods (winter and summertime),
- rooms have very different exposure to solar radiation,
- some rooms/offices were occupied very irregularly (meeting rooms, etc),
- no heating/cooling demand in the weekend.

Moreover, many rooms exhibit special behaviours with respect to the amplitude of the air temperature fluctuations. It makes it difficult to find a reliable pattern to identify sensor failures. That latter comment is illustrated on figure 6.12 which shows the fluctuations of the air temperature in room 221 from July 2007 to August 2008. Many spikes orientated downwards can be observed. They potentially reflect drops in the measured value of the air temperature or failures of the sensors. By looking more in details at the temperature drop occurring in November 2007 on figure 6.13 (top graph), together with the position of the cooling valve (middle graph) and the electricity demand of cooling system 2 (bottom graph), it can be observed that a drop of more than 3.5°C is experienced just before 6 pm, along with the shutdown of the cooling baffle. That drop lasts for almost one hour even though the cooling baffle remains shut meanwhile. In the present example, the most likely explanation is that the cooling baffle had been partially opened for a while and blew cold air into the room until the sensor was hit by a cold air flow. Nothing really explains that sudden drop but nothing allows us to think that the drop did not happen locally.

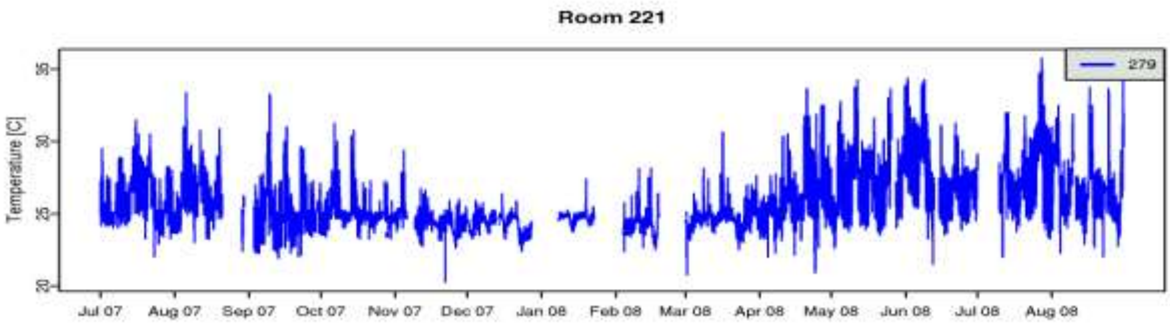


Figure 6.12. Air temperature in room 221 (July 2007 - August 2008).

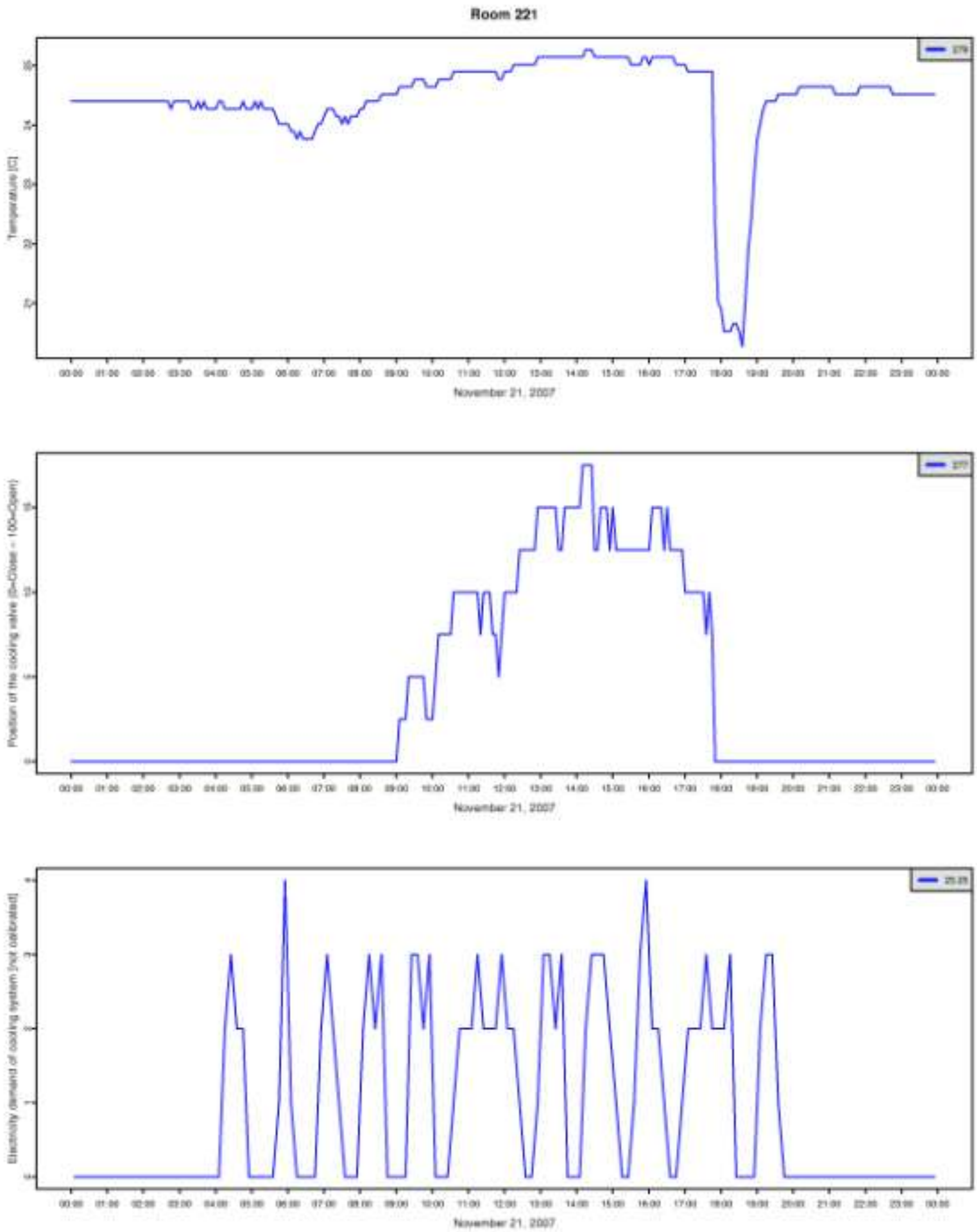


Figure 6.13. Air temperature in room 221 (November 21, 2007).

The example presented above was just one among many others and it still remains a challenge to understand the possible causes of such a sudden drop. Therefore, when nothing clearly indicates that there is a problem, not to remove those observations is a choice motivated by the need to conserve the local variability in the data.

6.1.6. Resampling and smoothing

Once data has been cleaned for outliers and other erroneous behavior, it needs to be transformed into a representation that can be used in a multivariate analysis. In such an analysis, original time series must be synchronized such that they can be merged into a multivariate time series with one equidistant timestamp. As an example, consider for instance measurements of a room temperature and measurements of the ambient temperature forming two separate time series. Now, one wants to estimate the correlation between the two variables. If the data loggers have recorded with exactly the same frequency and without offset, this task is simple. But what is more likely is that the two are recorded differently with respect to both frequency and offset, and points in the two time series cannot be directly compared since they are not recorded at the same time.

An interpolation can then be applied on one or both of the time series. In this work, kernel estimation - see (Härdle, 1990) and (Nadaraya, 1964) - has been applied to re-sample all measurements. Kernel estimation is a weighted average in a “sliding window”. The kernel that has been used is the Epanechnikov kernel with a total width of one hour such that measurements that are more than half an hour from the point to be estimated are neglected (see figure 6.14).

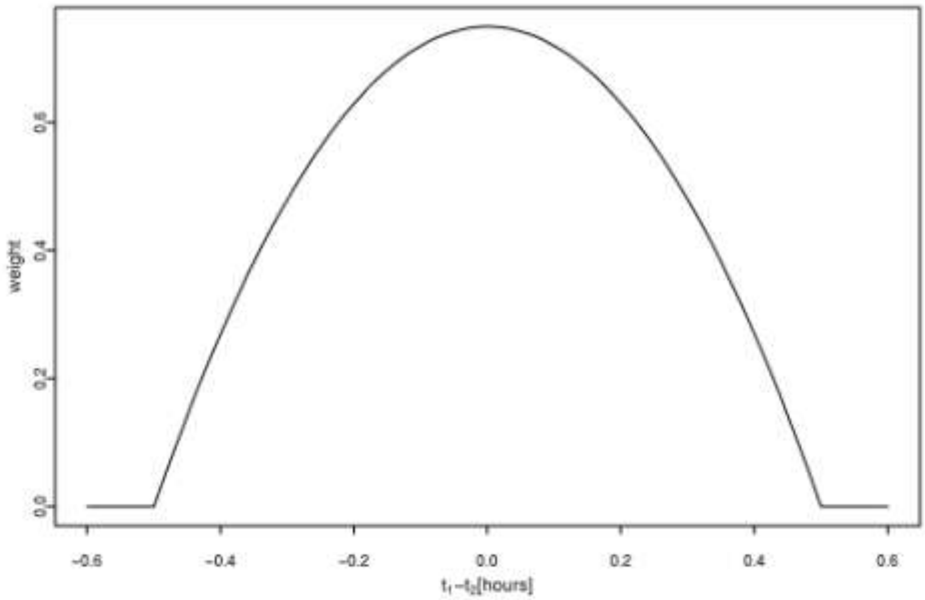


Figure 6.14. The Epanechnikov kernel of width one hour

6.1.7. Energy consumption

Three different time series of electricity consumption have been compared and two of them are available from the database. They are electricity to technical installations (time series 20), electricity demand for common installations provided by DONG Energy (time series 982), and manual readings of the electricity meter (not in the database).

The data from DONG Energy and the manual readings were inspected, and no outliers or suspicious behavior was found. The series from DONG Energy has a sample period of 1 hour, starts the first of August 2007 and ends on August 31, 2008. June 2008 is completely missing, but apart from that no data point is missing. The series represents power consumption of unit kW. The manual meter readings are approximately monthly and represent the cumulative consumption. The readings are done from the end of June 2007 until the beginning of September 2008. The monthly cumulated values based on the measurements from DONG Energy are quite identical with the monthly manual readings of the meter.

The measured electricity consumption (Time series 20) and the DONG Energy measurements are compared over a week (in February 2008) on figure 6.15. Note that the blue curve displayed has been differentiated and then multiplied by a factor 6. As shown, the two series logged exhibit the same diurnalites and very similar levels of power even though the measured electricity consumption (in blue on figure 6.15) is showing more volatility due to a smaller sampling resolution than the measurements from DONG Energy. Figure 6.15 shows that much information on the variation of the electricity consumption is lost when going from 5 minutely to hourly values. High frequency measurements are thus necessary when evaluating the dynamic behaviour of building and installations.

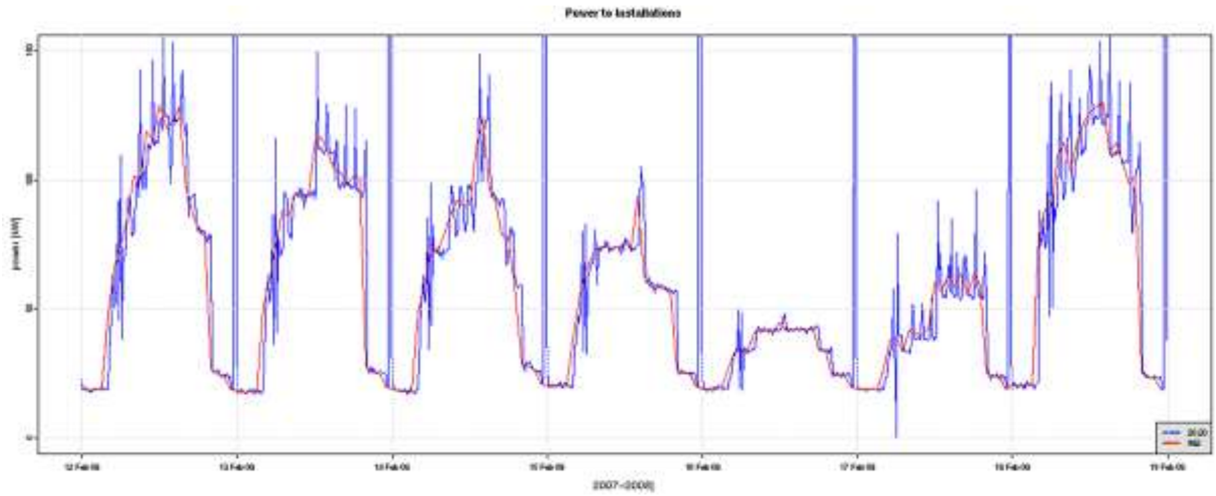


Figure 6.15. The electricity consumption in the database (time series 20 in blue) vs. the measurements from DONG Energy (time series 982 in red).

Figure 6.16 represents the cumulative electricity consumption (time series 20 not differentiated). It seems that every day, some weird measurements appear. Are these jumps the result of errors in earlier measurements or are they erroneous themselves? The periodic jumps before midnight in the measured data from the database are believed to be errors due to recalibration. Based on a histogram of the data, a threshold value (50 kWh) was decided to distinguish between difference that can be explained by consumption and larger jumps. The jumps were then removed.

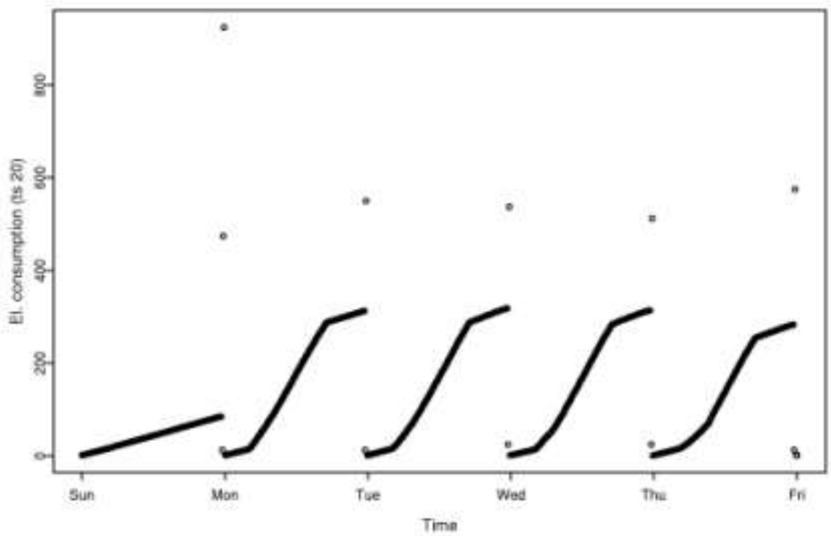


Figure 6.16. The cumulated electricity consumption in the database. The period shown is from 2008-04-13 to 2008-04-17.

6.1.8. District heating

Both a plot of the full time series of district heating demand and an extract (22-28/10/2008) are shown on figure 6.17. This time series is seen not to have the same periodic jumps as the electricity.

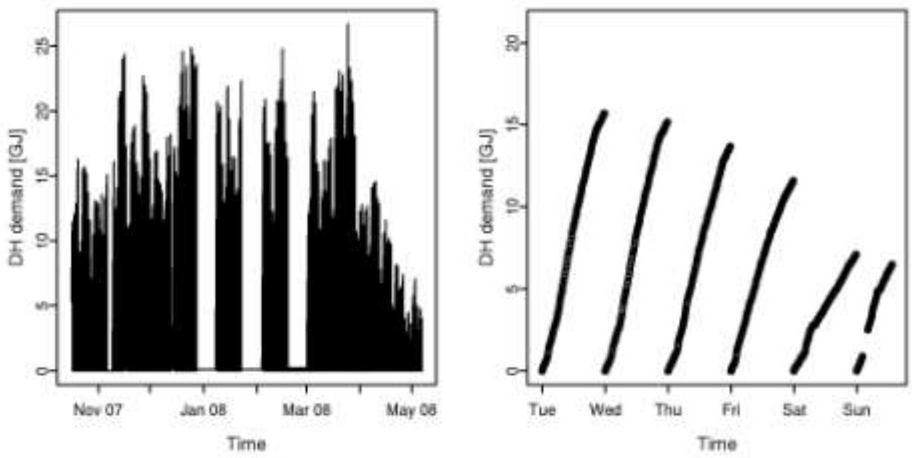


Figure 6.17. District heating demand (time series 21).

The data from the database is compared with the observations manually read from the meter. These time series are shown on figure 6.18.

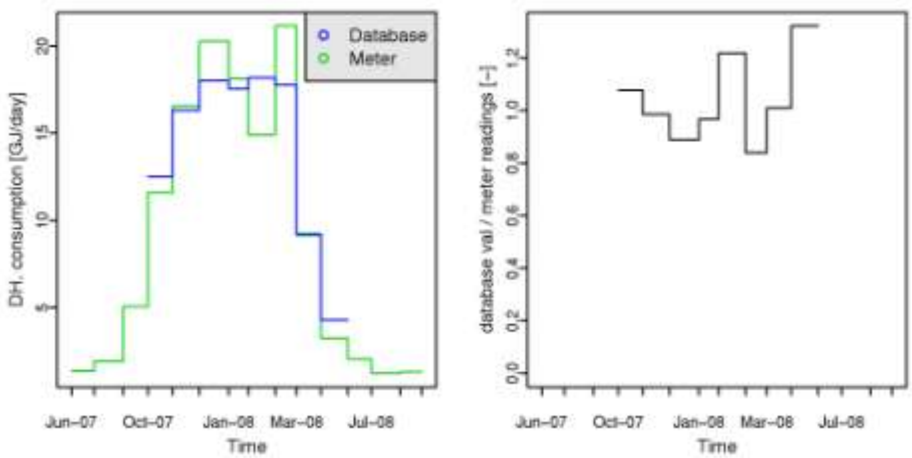


Figure 6.18. The monthly district heat consumption based on the two different time series (figure on the left). The ratio between the two time series (figure on the right).

These measures are comparable, and they only differ by a factor two in the last period where data are only available for 8 days from the database.

6.1.9. Recommendations on data quality issues

The outcomes of statistical or any empirical analysis are often conditioned upon the quality of the data. Indeed, high quality data sets ensure a better understanding and a higher reliability when it comes to interpret the results of a statistical analysis. The main problem that we identified in this project was the lack of accuracy of many sensors located in the offices. It seems that they poorly captured the air temperature fluctuations resulting in a lack of variability in the data. One way to overcome this problem is to resample the data at a larger temporal resolution (1 hour instead of the original 5 minutes) either using a simple averaging procedure or smoothing techniques. But information on the dynamical behaviour of the building and installations may be lost.

Regarding the control strategy of the Building Management System, if one assumes that the heating or/and the cooling settings in the offices are governed by the signal sent by inaccurate sensors, it may generate overheating (when the air temperature read by the sensor is significantly lower than it is in reality) or overcooling (when the air temperature read by the senor is significantly larger than it is in reality). It was reported in chapter 5 that the measured air temperature could vary up to 2°C in between the BMS and the special indoor climate sensors. These differences in the measurement could be explained by the respective locations of those sensors in large open space offices but also by inherent differences in their respective level of accuracy. One possible way to prevent this problem would be to install more than one single sensor per room and cross validate them by comparing their respective measurements.

6.2. Multivariate statistics

Statistical methods which are normally useful in multiparameter sensors applications often aim at concentrating the information from several sensors, or a few statistically generated signals, or even decomposing a series or a group of series into different components or parts: a trend, seasonalites, diurnalites and residuals (the remaining information after removing all other parts). Many examples that have neither been implemented nor tested in this project are reviewed in subsection 6.2.4. These methods would require to be finely tuned according to the type of data to be processed and would be too time-consuming. A more straightforward method, often referred as an exploration or projection method, is the Principal Component Analysis (PCA). It is widely used to show the underlying structure of multidimensional data. A very comprehensive introduction on PCA, based on a non-mathematical approach, is given in (Esbensen, 2006).

6.2.1. Principal Component Analysis

Principal Component Analysis can be performed for a variety of reasons, one could consider its use in one of three following ways:

- Arguably the most common use is in terms of dimension reduction. Principal component analysis can be thought of as a data analytic method which provides a specific set of projections which represent a given data set in fewer dimensions. This has obvious advantages when it is possible to reduce dimensionality to two or three as visualization becomes very straightforward.
- Another reason for conducting principal components analysis is to transform correlated variables into uncorrelated ones. Whilst univariate data can be standardized by centering and scaling, in a multivariate context one may also wish to "standardize" the correlation between variables to zero.
- The final reason for the technique is that it finds linear combinations of data which have relatively large (or relatively small) variability.

The PCA procedure is briefly described on figure 6.19.

		Input variables			
		X_1	X_2	…	X_R
Measurements (or observations)	1	$x_{1,1}$	$x_{2,1}$	…	$x_{R,1}$
	2	$x_{1,2}$	$x_{2,2}$	…	$x_{R,2}$
	3	$x_{1,3}$	$x_{2,3}$	…	$x_{R,3}$
	⋮	⋮	⋮	⋮	⋮
	n-1	$x_{1,n-1}$	$x_{2,n-1}$	…	$x_{R,n-1}$
	n	$x_{1,n}$	$x_{2,n}$	…	$x_{R,n}$

PCA

(Transformation of a number of possibly correlated variables $X_1, \ldots, X_R$ into a smaller number of uncorrelated variables called principal components $Y_1, \ldots, Y_M$ with $M \leq R$)

		Principal components (output variables)			
		Y_1	Y_2	…	Y_M
Measurements (or observations)	1	$y_{1,1}$	$y_{2,1}$	…	$y_{M,1}$
	2	$y_{1,2}$	$y_{2,2}$	…	$y_{M,2}$
	3	$y_{1,3}$	$y_{2,3}$	…	$y_{M,3}$
	⋮	⋮	⋮	⋮	⋮
	n-1	$y_{1,n-1}$	$y_{2,n-1}$	…	$y_{M,n-1}$
	n	$y_{1,n}$	$y_{2,n}$	…	$y_{M,n}$

Figure 6.19. Summary of the PCA procedure.

The procedure consists in projecting the observations of R variables in a new space of fewer dimensions than the original one while trying to account for as much information (or variance) as possible. The number of dimensions of the original space is equal to the number of input variables, that is to say R. The first principal component, Y_1, is given by the linear combination of the input variables $X = [X_1, \ldots, X_R]$ with the largest possible variance (variance = relevant information in the data), and each succeeding component accounts for as much of the remaining variability as possible and are uncorrelated with the previous components (see figure 6.20).

$$Y_1 = p_{11}X_1 + \ldots + p_{1R}X_R$$
$$\ldots$$
$$Y_M = p_{M1}X_1 + \ldots + p_{MR}X_R$$

Figure 6.20. The output variables are a linear combination of the input variables.

6.2.2. The data

The original set of data is in the following composed of 63 air temperature series logged in the rooms of the first and second floors over the period 01/07/2007 – 31/08/2008. Even though, as reported in section 6.1, measurements are not very reliable in term of short term variability, we make the naive assumption that they are and do not remove any of the sequences of constant readings. However, in an attempt to lessen the inconvenience regarding the lack of measurement variability, data are averaged over one hour intervals.

As stated in chapter 1, the number of input variables or signals is in theory infinite. In the present PCA, there are 63 input signals which is already a significantly large number to demonstrate the ability of the method to capture the underlying structure in the data. With a deeper knowledge on the respective functionalities of each room in the building, one could think of feeding the method with any relevant measurements. The input signals do not necessarily need to measure the same parameter of the building and many different sources of information can be combined. For instance, it would be possible to mix input signals as measured solar radiations, air temperature, CO_2 level, air flows and relative humidity.

As almost all statistical methods, PCA is very sensitive to outliers and missing values. That is why, to overcome these problems, we restrict the period of investigations to 01/03/2008 – 30/04/2008. There is no missing value (but one in March 30, 2008 when time switches from winter to summer time) and almost no outliers.

The original air temperature distributions are summarized on figure 6.21 where one boxplot per series is depicted. A boxplot provides a statistical summary of a distribution through it's:

- lower quartile (the lower bound of the box), the 25th percentile,
- median (the central mark of the box) which by its position depicts the symmetry or skewness of the distribution,
- upper quartile (the upper bound of the box), the 75th percentile, which together with the lower quartile define the interquartile range (it means that 50% of the observations stretch within the interval defined by the bounds of the box) which gives an estimation of how spread out the data are,
- whiskers (the hinges on the box) which extend to the most extreme data point which is no more than 1.5 times the interquartile range from the box; it gives a graphical overview of the tails of the distributions,
- potential outliers (the single data point above the upper whisker and below the lower one) which are consider as potential outliers.

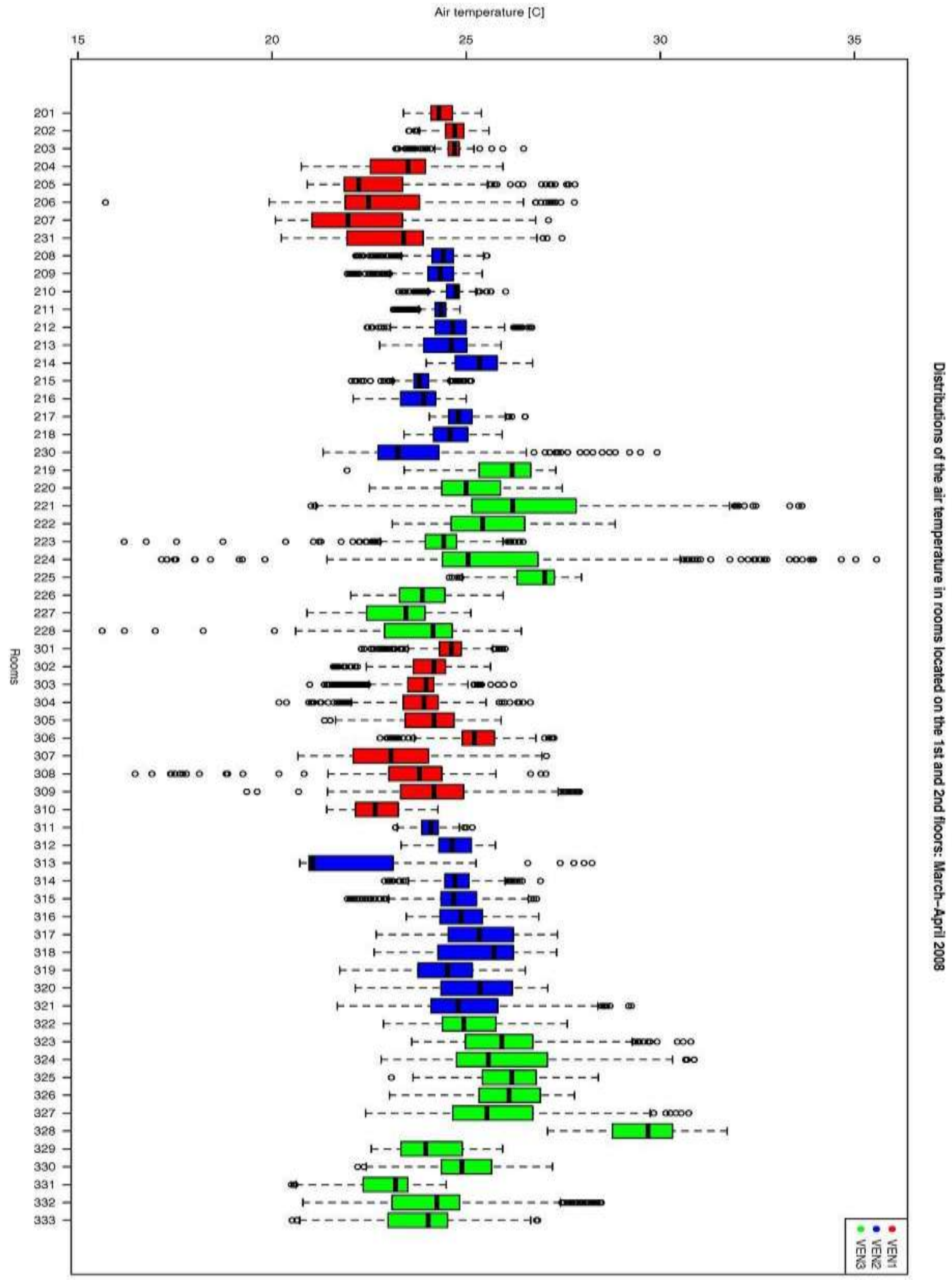


Figure 6.21. Summary of the air temperature distributions of rooms located on floor 1 and 2.

Boxplots usually provide a much more robust (less sensitive to extreme values) description of a given distribution than a combined description by the mean, variance, minimum and maximum values.

On figure 6.21, the boxplot color code is as follows: red for rooms ventilated by system 1, blue for rooms ventilated by system 2 and green for rooms ventilated by system 3. Many observations can be made from this figure:

- rooms 204, 205, 206, 207 and 231 have a median values among the lowest of all rooms and have very skewed (asymmetric) distributions (the median mark is not located in the center of the box) meaning that there are periods of time when the air temperature significantly deviates from its potential steady behavior (shift in the level of air temperature), this indicates that the mean temperature in those rooms is not constant over time,
- rooms located on the first floor and ventilated by system 2 (room 208, …, 218, 230) have relatively narrow interquartile range but for room 230, this means that the amplitude of the air temperature fluctuations is rather small,
- air temperature distributions of rooms 219, … , 224 are very spread, indicating large fluctuations of the temperature,
- room 313 has the most singular distribution with a very low median value and very skewed towards high temperature,
- room 328 has the largest median value of all rooms (see also chapter 5),
- among the rooms located on the second floor and ventilated by system 3, the air temperature in the rooms located in the western part of the building (323, 324, 325, 326, 327) is much higher than in the room in the northern part, this could be explained by the type of rooms (meeting rooms in the northern part vs. offices in the western part) or by a higher exposure to solar radiations in the western part than in the northern one.

It is worth mentioning that these comments on figure 6.21 agree and confirm some of the observations summarized in table 5.3 and illustrated on figures 5.37-48. The tools to summarize the distribution of the air temperature in rooms are different (Cumulative distribution function in chapter 5 vs. boxplot) but lead to some similar observations.

One of the reasons to apply PCA is to transform a number of possibly correlated variables X_1, … , X_R into a smaller number of uncorrelated variables. Figure 6.22 shows two examples of highly correlated “input variables”. Correlations coefficients are larger than 0.9 in both examples. On the left part of the figure, the linear relationship in between the air temperature in rooms 201 and 202 is depicted. The same type of relationship in between rooms 323 and 324 is illustrated on the right part of the figure. Somehow, this is intuitive since these rooms are adjacent and consist of large rectangular open space offices separated by a wall with openings at both ends. There is then an air flow in between these offices.

Outliers are carefully handled but once again, it turns out to be very difficult to assess whether we are right in doing so or not. Figure 6.23 illustrates our difficulties and shows the air temperature in two adjacent rooms: 223 and 228. If one looks at the two plots separately, one could think that the sudden drops correspond to erroneous measurements. However, when one looks at both plots at a time, it appears clear that the same event was identified in the 2 rooms, supporting the idea that it really happened. In that case, no measurement was removed. Finally, very few obvious outliers were found: one can be easily spotted for room 206 (see figure 6.21), for instance.

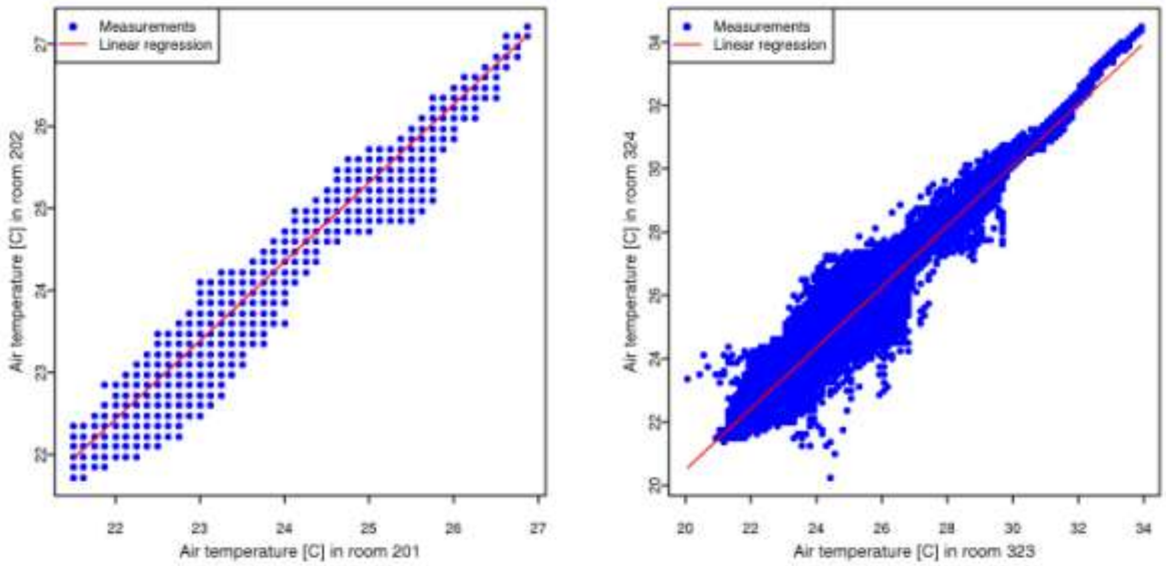


Figure 6.22. Correlations of the air temperature in between adjacent rooms.

6.2.3. Interpretation of the results

Because principal components analysis seeks to maximize the variance, it can be highly sensitive to scale differences across variables. Thus, it can be a good idea to standardize the variables (which means divide them by their respective standard deviations). PCA was applied to both standardized and non standardized data and the results were quite similar. Therefore, we only report the results of the PCA applied to standardized data.

The basic results from the PCA of the 63 air temperature series are shown in table 6.3 (to make it clearer, we only present the results for the first six components). Various statistics are reported in table 6.3. The main idea is that each principal component concentrates a share of original variance. A look at the table reveals that the first principal component PC1 accounts for a substantial share of variance in the data: 56.3% (top row with numbers in table 6.3). The second PC accounts for 9.3% of the original variance. In total, the first 6 components (out of 63) explain more than 80% of the original variance of the input variables (second row in table 6.3). It means that we can summarize 80% of the 63 original variable variance with only 6 new variables.

It is often instructive to investigate the relationship between the principal components and the original variables. One way to do this is to look at the contributions of the original variables to the generated principal component and the original variables. These correlations are referred as the principal component loadings and are reported in table 6.3 (third row and down in table 6.3).

The values highlighted in grey in table 6.3 reflect rooms that contribute largely to the principal components. In other words, rooms which have a singular value with respect to one of the principal components, a value that deviates significantly from the values of the other rooms over a given principal component. The larger the loadings, the more the rooms contribute to a given principal component. The values highlighted in table 6.3 differ across the principal components and there is no absolute threshold. Rather than targeting at single room, we have tried to identify groups of rooms among the ventilation systems that strongly contributed to the principal components.

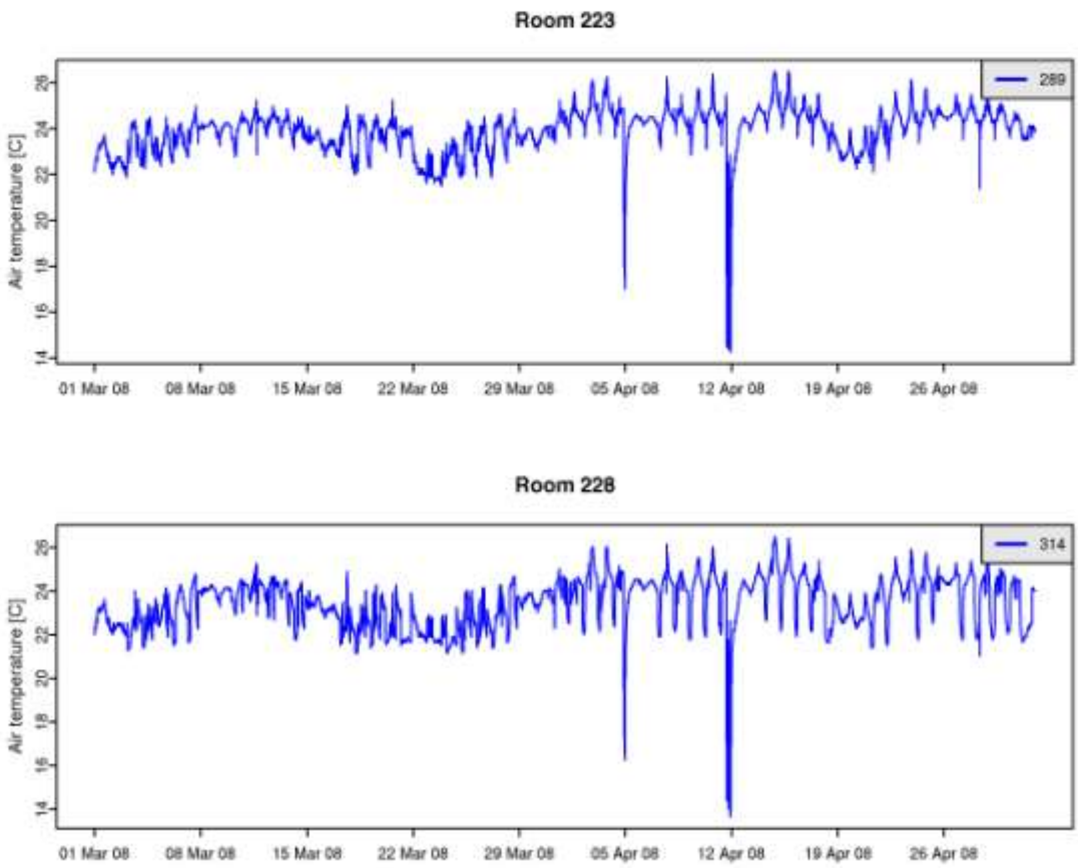


Figure 6.23. Air temperature in two adjacent rooms: outliers or not?

		PC1	PC2	PC3	PC4	PC5	PC6
	Explained Variance [%]	56.3	9.3	5.4	4.2	3.4	2.1
	Cumulative variance [%]	56.3	65.6	71	75.2	78.6	80.7
Original variables (Air temperature in rooms)	**201**	0.16	-0.02	0.09	-0.06	0.04	-0.06
	202	0.15	-0.04	0.09	-0.11	0.06	-0.02
	203	0.13	0.01	0.1	-0.2	0.02	0.07
	204	0	**0.33**	0	0.02	-0.1	**-0.33**
	205	0.1	**0.24**	**-0.16**	0.05	-0.05	**-0.28**
	206	0.06	**0.28**	**-0.26**	0.06	-0.07	**-0.2**
	207	0.11	**0.19**	**-0.16**	-0.03	**0.18**	-0.12
	231	0.03	**0.36**	0.01	0.02	-0.02	**-0.26**
	208	0.15	0.01	**0.17**	0.01	-0.13	-0.01
	209	0.15	-0.04	**0.15**	-0.01	-0.1	0
	210	0.14	0.07	**0.19**	-0.11	-0.06	0.08
	211	0.13	0.06	0.14	0.07	-0.05	-0.04
	212	0.13	-0.03	0.09	**0.2**	**-0.19**	-0.05
	213	0.15	0.02	0.1	0.11	-0.15	0.06
	214	0.14	0.08	0.05	0.07	-0.17	0.12
	215	0.09	0.06	-0.07	-0.1	**-0.28**	**0.34**
	216	0.11	-0.01	-0.03	-0.06	**-0.33**	**0.26**

	217	0.15	0.06	0.04	0.03	-0.11	0.09
	218	0.14	0.04	0.07	0.06	-0.16	0.06
	230	0.13	0.14	-0.07	0.05	0.07	0.15
	219	0.14	-0.06	0.03	-0.05	0.15	0
	220	0.15	-0.1	-0.07	**0.15**	0.09	-0.02
	221	0.13	0.04	**-0.17**	**0.22**	0.16	0.1
	222	0.15	-0.02	-0.09	**0.17**	0.14	0.06
	223	0.09	0.12	-0.05	**-0.25**	0.08	0.04
	224	0.11	0.12	**-0.17**	**0.21**	0.12	0.12
	225	0.15	-0.03	-0.04	-0.03	0.08	0.13
	226	0.14	-0.13	-0.06	0.11	0.12	0
	227	0.12	0	**-0.24**	-0.14	0	0.01
	228	0.1	0.01	-0.11	**-0.26**	0.09	0.01
	301	0.11	**-0.17**	0.07	-0.11	0.06	-0.18
	302	0.12	**-0.2**	0.04	-0.07	0.1	**-0.2**
	303	0.11	0.06	**0.18**	**-0.21**	0.15	-0.04
	304	0.11	-0.02	0.13	-0.13	0.11	-0.13
	305	0.12	**-0.17**	0	-0.03	-0.06	**-0.21**
	306	0.14	-0.05	0.01	-0.08	-0.02	-0.16
	307	0.08	**0.19**	**-0.21**	0.01	**-0.23**	-0.06
	308	0.1	0.09	-0.04	-0.13	0.02	-0.05
	309	0.1	-0.07	**-0.18**	-0.16	0.09	-0.11
	310	0.05	-0.02	-0.09	**-0.35**	-0.02	0.15
	311	0.15	0.04	**0.19**	-0.08	0.07	-0.03
	312	0.15	-0.04	0.13	0.03	0	-0.13
	313	0.01	**0.25**	0.06	**-0.25**	**0.21**	**0.23**
	314	0.14	-0.01	0.12	-0.07	-0.07	-0.09
	315	0.15	0.03	0.15	-0.02	-0.01	-0.03
	316	0.15	0.1	**0.17**	-0.03	0.03	0.05
	317	0.15	0.02	0.1	0.14	-0.01	0
	318	0.15	-0.05	0.06	0.15	-0.08	-0.02
	319	0.14	-0.06	0.06	0.03	**-0.23**	-0.04
	320	0.15	-0.05	0.09	0.11	-0.08	-0.07
	321	0.14	0.01	-0.03	0.15	0.01	0
	322	0.15	-0.1	-0.06	0.14	0.18	0.04
	323	0.14	0.07	-0.03	0.13	0.18	0.14
	324	0.14	0.08	-0.08	0.14	0.16	0.17
	325	0.14	0.03	-0.01	0.04	0.1	0.03
	326	0.15	-0.04	-0.05	0.03	0.07	0.04
	327	0.12	0.06	-0.03	0	0.05	0.15
	328	0.08	**-0.29**	-0.1	0.1	0.16	-0.07
	329	0.13	0.09	**-0.2**	-0.14	-0.05	0.05
	330	0.12	**-0.16**	**-0.2**	-0.1	-0.04	-0.09
	331	0.12	-0.07	**-0.21**	-0.14	-0.13	-0.05
	332	0.05	**-0.22**	**-0.29**	-0.06	**-0.27**	-0.05
	333	0.11	**-0.19**	**-0.2**	-0.07	-0.1	-0.01

Table 6.3. Loadings of the PCA

The information reported in table 6.3 can be represented in a graphical way. Figures 6.24, 6.28 and 6.29 show scatter plots of the loadings of the first principal component versus those of the second and third principal components. That way, it is faster and easier to interpret the information carried out by the principal components when the number of original variables is large. Moreover, looking at the information provided by the PCA is also another way to evaluate the relative performance of rooms with respect to the indoor climate.

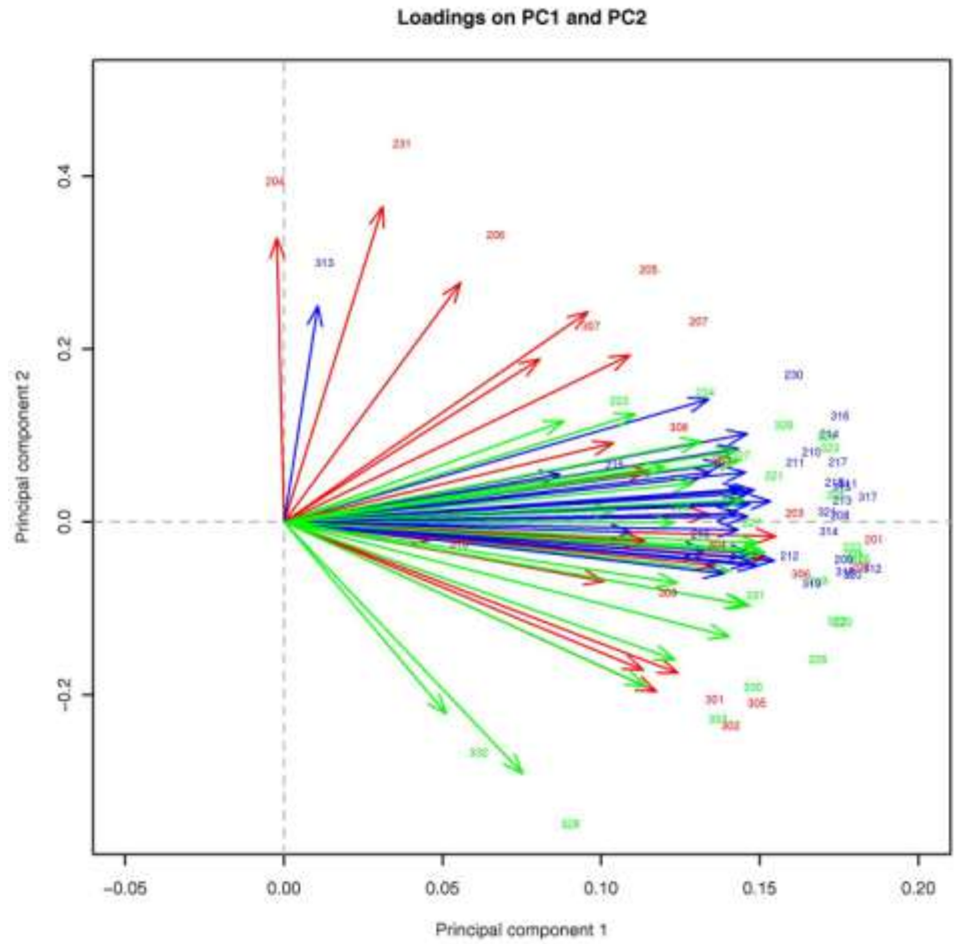


Figure 6.24. Loadings of the first and second principal components (PC1 & PC2).

A look at the loadings confirms that the first principal component is a positive combination of a large majority of the 63 original air temperature series. In contrast, series logged in rooms 204, 313, 231, 206, 332 and 328 seem to have behaviors that deviate from the mean behavior (see figure 6.24) since they almost do not contribute to the first principal component.

Figure 6.25 shows the (scaled = centered + standardized) first component plotted (in red) along with 5 (scaled) air temperature series drawn randomly. The five series come from rooms 209, 215, 220, 323 and 330. One can clearly see that the first component (in red on the figure) captured both the short term variations (diurnalites) and the more long term variations of the averaged air temperature in the building. The first principal component PC1 can, therefore, be interpreted as the mean air temperature of the rooms located on the first and second floors. The first principal component is very useful to identify rooms where the air temperature deviates temporarily and significantly from the mean behavior of the rooms in the building. For instance, one can observe a sudden drop of the air temperature in room 215 during April 2008 which calls for further investigations.

PCA is a deterministic approach since the new variables (the principal components) are computed as a linear combination (with constant coefficient) of the older variables. For instance, one could interpret the first principal component as the response of the air temperature in the building to the ambient air temperature variations. The linear correlation coefficient in between the first PC and the ambient air temperature is equal to 0.62 which shows that the proposed modeling approach does not capture all the information (see figure 6.26). Indeed, ideally, the modelling approach for such a problem should be dynamical, accounting for changes in the process governing the air temperature fluctuations (see the methods described in subsection 6.2.4). However, PCA remains very informative to identify rooms with singular air temperature fluctuations.

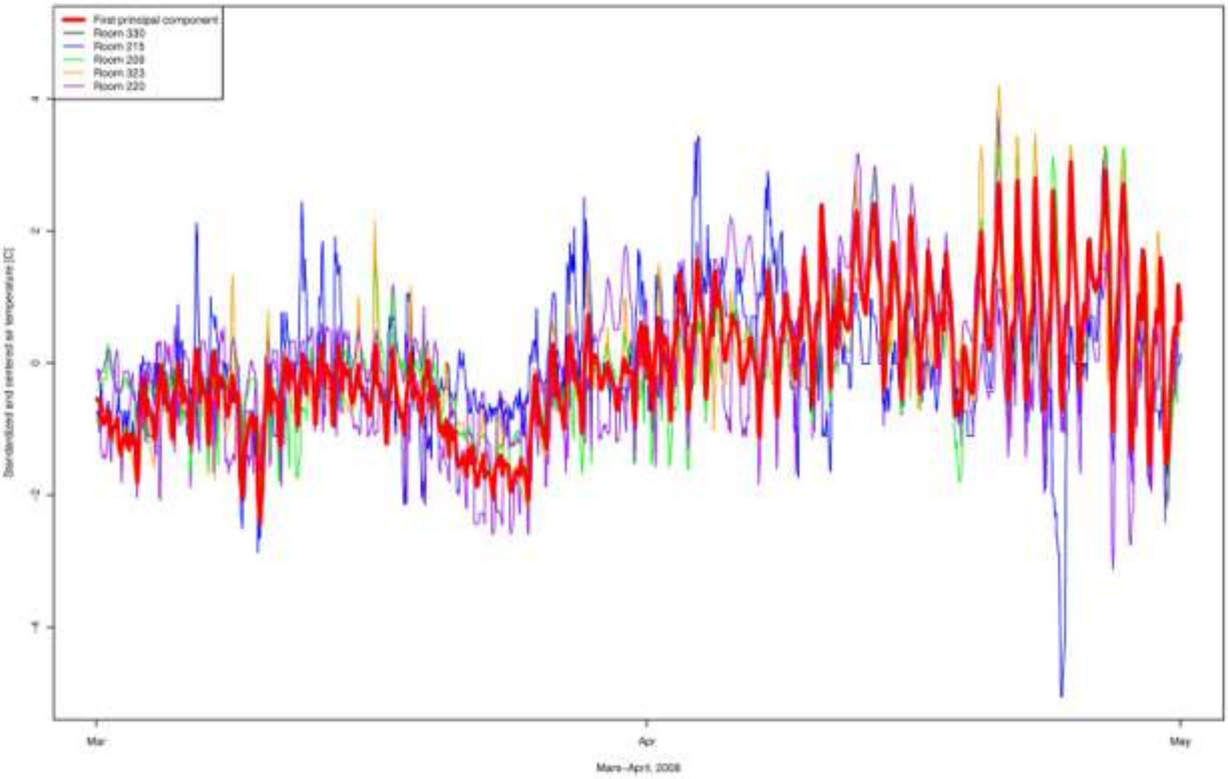


Figure 6.25. The first component (PC1) is a linear combination of the original variables.

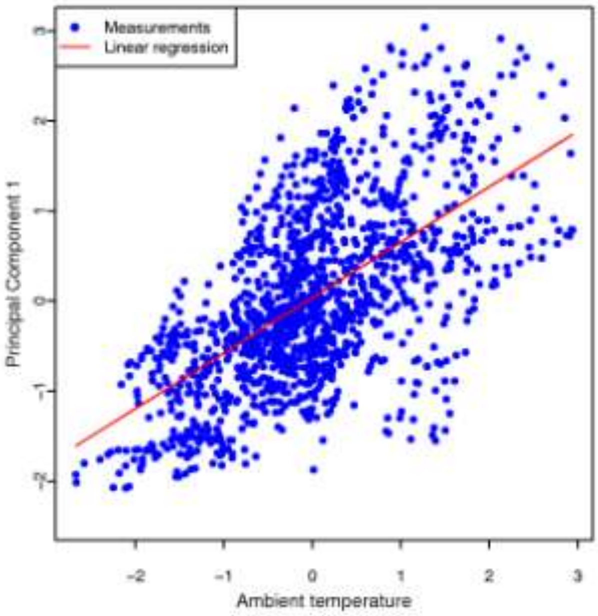


Figure 6.26. Ambient temperature vs. PC1 – March & April, 2008.

If we disregard rooms 313 and 204 for a moment, one can from table 6.3 see that the second principal component PC2 is associated to small meeting rooms with windows orientated to the north. Rooms 204, 205, 206, 207, 231 and 307 (all ventilated by system 1) positively contribute to the second principal component whereas rooms 330, 331, 332 (ventilated by system 3) contribute to it in the negative direction (which does not mean “in a negative way”). Figure 6.27 shows the air temperature of rooms 231, 206, 332 and 333. Both rooms 231 and 206 exhibit regular air temperature fluctuations until the 19^{th} of April but from then, they experience much higher peaks of temperature (see figure 6.27). It seems that those two rooms have an extreme response to the increasing ambient temperature at the end of April. It is the opposite that rooms 332 and 333 experience: air temperature fluctuations are very irregular (due to solar radiation) until the middle of April (room 332 is especially very warm from the end of March to mid April) and from then, the mean temperature drops significantly. Temperature set values for each of these rooms were checked and were found to be changed only in the last two days of April but it cannot explain the increase or drops of temperature from mid April.

Therefore, the second principal component is associated with rooms where the air temperature changes significantly after mid April.

From figure 6.28, one can easily notice that almost all rooms ventilated by system 2 (with loadings drawn in blue) positively contribute to the third principal component PC3 whereas almost all rooms ventilated by system 3 (with loadings drawn in green) contribute to PC3 in the opposite direction. We therefore interpret the third principal component as the reflect of the differences in between ventilation system 2 and 3. Any room that is ventilated by system 3 and that would positively contribute to the third component PC3 should be considered as highly suspicious. And, any room that is ventilated by system 2 and that would negatively contribute to the third principal component PC3 should be considered as highly suspicious. PC3 does not bring any information on how to further distinguish rooms ventilated by system 1 (in red on figure 6.28).

If the first component PC1 is associated with the mean response of the building to the ambient temperature fluctuations, one can see that there are a few variables (rooms) which almost do not contribute to it such as rooms 204 and 313 whereas these 2 rooms contribute significantly some of the next components, PC2 or PC3 for instance. These two rooms are quite likely to be used as printer or server rooms and hence have very specific behavior. It can be seen on figures 6.24, 6.28 and 6.29 that the loadings of these 2 rooms have very different loadings than the other rooms. It is how the PCA translates the special behavior of these rooms. To some extent, one can observe on figure 6.29 that the loading of room 310 on the fourth principal component PC4 is also significantly different than the other rooms. PCA has identified room 310 as different to some extent. Indeed, relatively high temperatures (with respect to the mean temperature in this room) were experienced at the end of March and beginning of April (see figure 6.30).

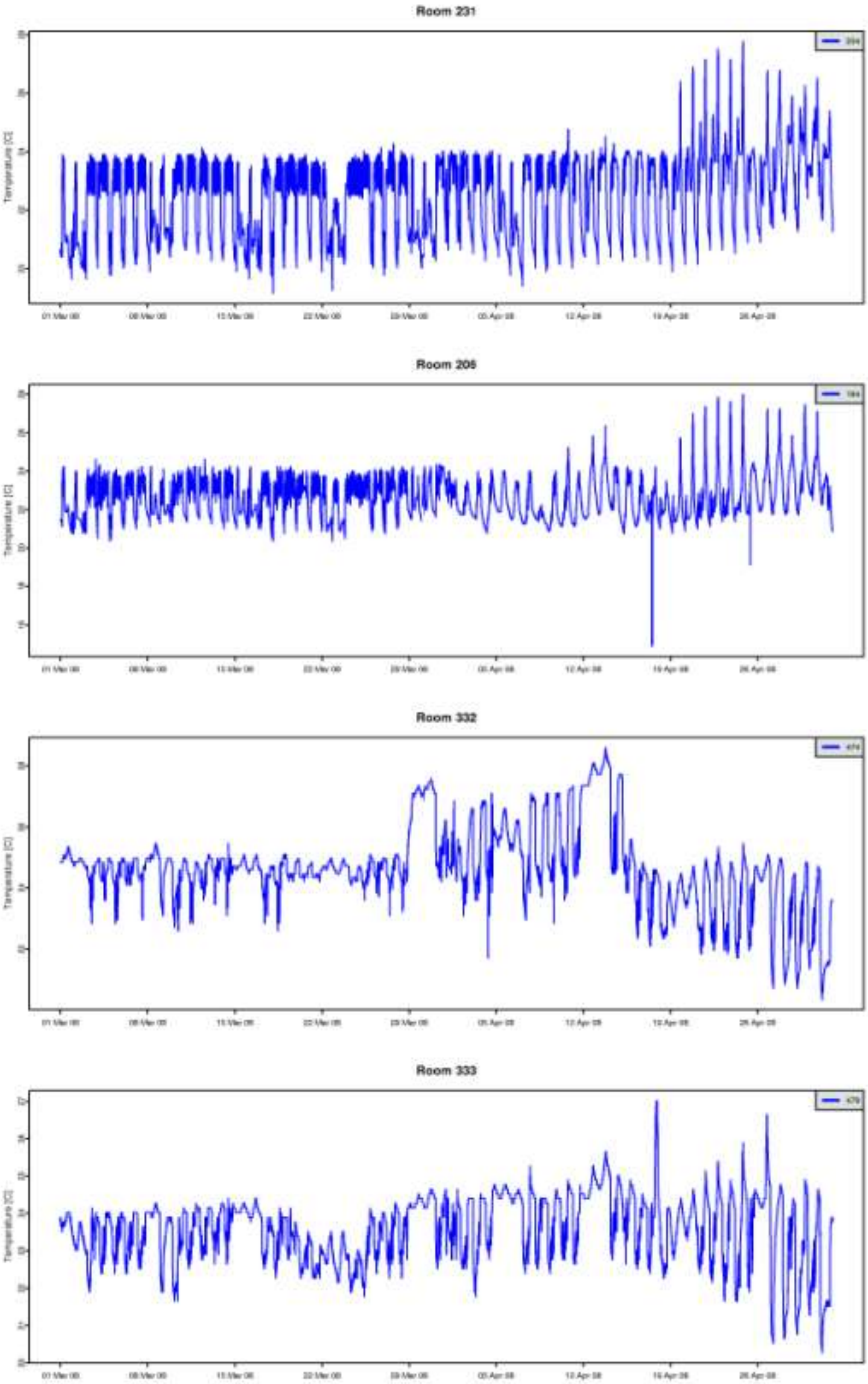


Figure 6.27. Air temperature changes after mid April.

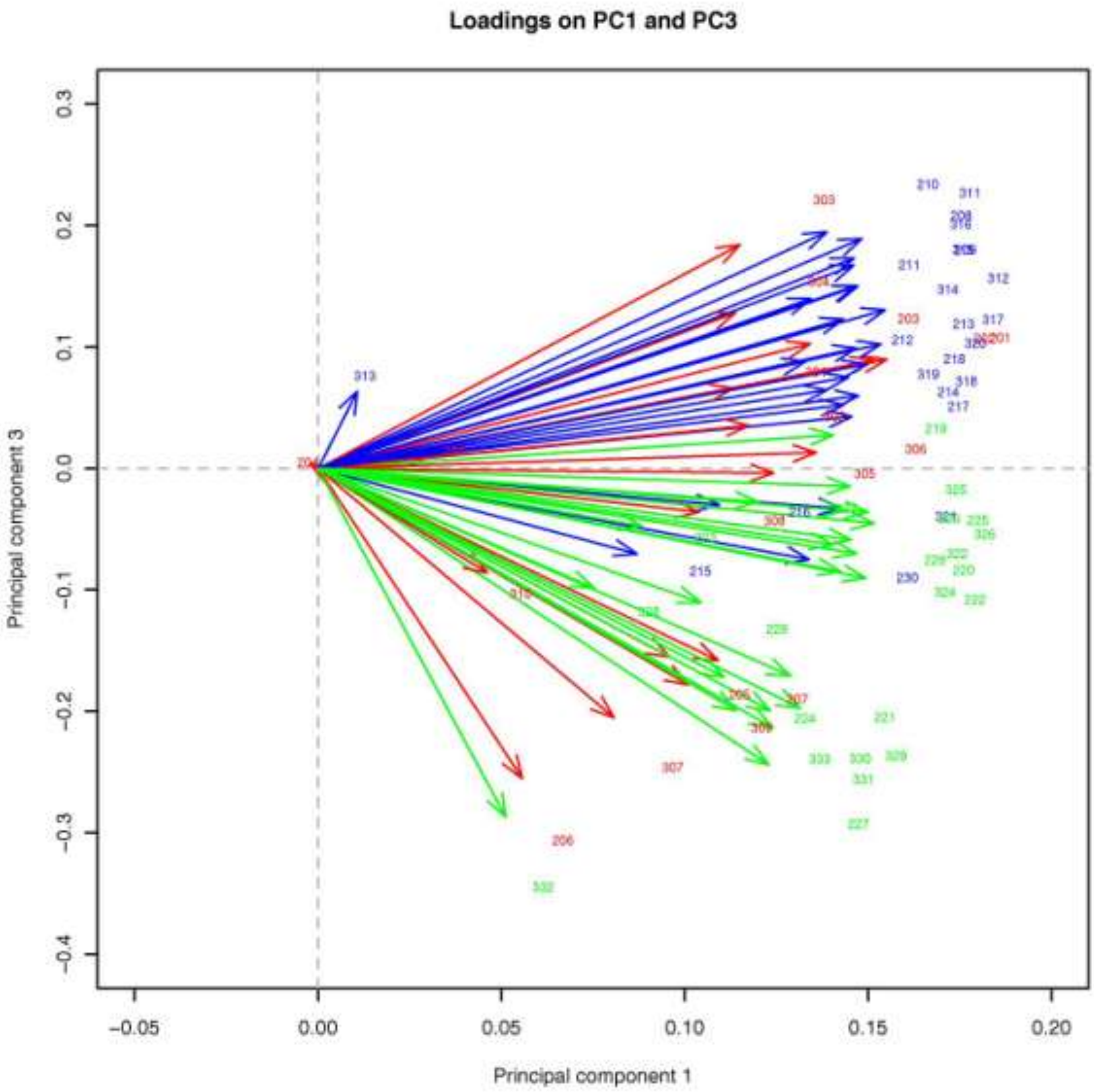


Figure 6.28. Loadings of the first and third principal components (PC1 vs. PC3).

6.2.4. Summary of the analyses of PCA

Principal Component Analysis manages to summarize more than 80% of the variance of the 63 original variables within 6 news variables. These new variables called Principal components (PC) allow identifying or observing various features of the building. The first principal component PC1 allows observing the mean air temperature fluctuations in the 63 rooms. It is then possible to identify rooms with air temperature fluctuations of large amplitude relatively to the mean behavior. PC2 is very useful to identify rooms with abnormal (or significantly different) behavior such as rooms 204, 206, 313 and 231 for instance. It also identifies rooms whose behavior changes after mid-April. PC3 reveals differences in the behavior of rooms ventilated by system 2 and 3. PC3 is positively associated with rooms ventilated by system 2 whereas it is negatively associated with rooms ventilated by system 3.

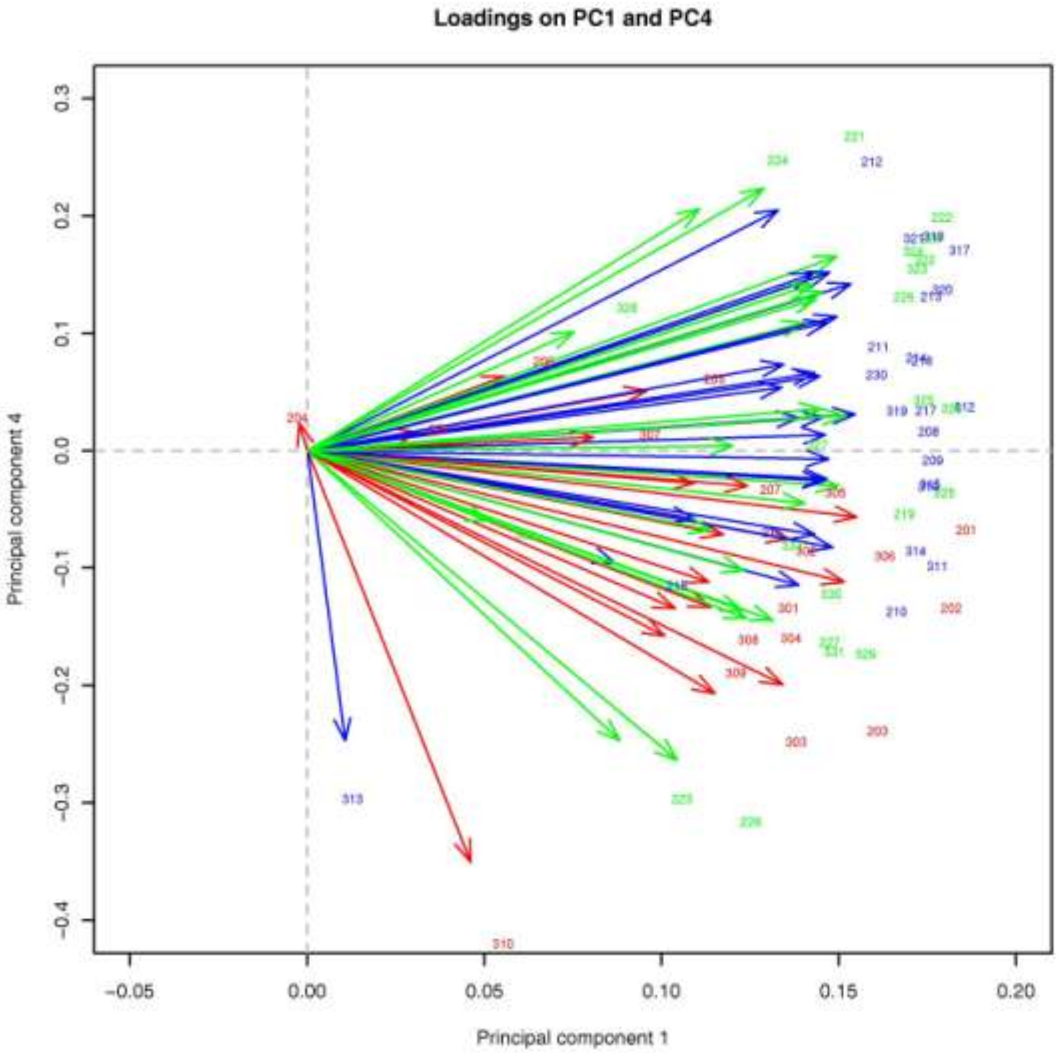


Figure 6.29. Loadings of the first and fourth principal components (PC1 vs. PC4 **).**

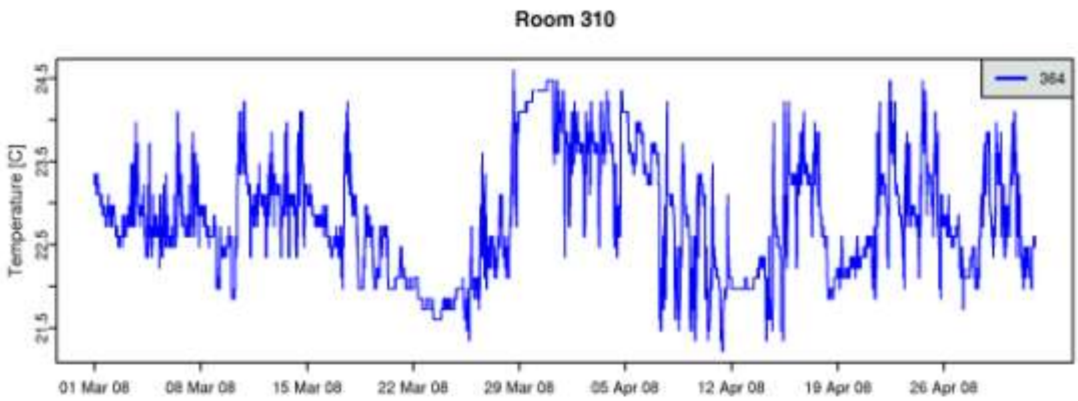


Figure 6.30. Air temperature in room 310 – March & April, 2008.

6.2.5. Future work and other methods

Various statistical tools or techniques were introduced throughout this project: cumulative distribution function (also called cumulative frequency curve in chapter 5), kernel estimation, boxplots, principal component analysis (see section 6.2), etc. Each of them was used to tackle a different problem and even though some of them have led to a better understanding and characterization of the building heating system, very few of them would be operational today in 2010. They all call for further developments and tests before one tries to make them operational.

The first step to a better heating control strategy was identified in section 5.6 and it is to categorize the rooms with respect to their respective requirements regarding thermal comfort. One could think of implementing different control strategy depending on their respective functionalities (server or printer rooms, large open space offices, meeting rooms, individual offices). Table 5.3 provides some results of a visual classification of the thermal comfort of rooms, based on the comparison of the room temperature cumulative distribution functions. A similar tool, the boxplot was introduced later on, in section 6.2, and could also be used for the same purpose as well as identifying outliers. So far, the drawback of these 2 tools is that no automated procedure has been developed and a visual evaluation needs to be performed. However, there are some statistical methods which could overcome this problem and help decision makers.

When it comes to automatic classification, statisticians or statistic practitioners often think of cluster analysis (Hair et al. 2009) which is an easy-to-use method for unsupervised learning (when one seeks to determine how the data are organized). It includes different algorithms for grouping objects of similar kind into respective categories. The objects (the rooms for instance in the present framework) could then be sorted into groups in a way that the degree of association between two rooms is maximal if they belong to the same group and minimal otherwise. However, this method neither aims at explaining the respective features of the sorted objects within each group nor provides any interpretation of these groups. In that respect, discriminant analysis looks much more convenient (Hair et al. 2009). This is a technique for classifying a set of objects into predefined classes. In that way, it would be possible to build on the knowledge accumulated during this project, the classification summarized in table 5.3 for instance, instead of starting all the analysis and researches from scratch.

Furthermore, as reported in the introduction of section 6.2, statistical methods which normally are useful in multiparameter sensors applications often aim at decomposing a series or a group of series into different components or parts. Among these methods, state space models and related tools like the ordinary Kalman Filter are often used to estimate non measured or non observable states of the system such as the heat accumulated in the building structure and could be used to optimize the control strategy. An illustration of the usefulness of the Kalman filter is given in Kummert et al (2009). It is shown how to anticipate and better account for both internal and external sources of disturbances which lead to unexpected temperature gains or drops. This approach aims at regulating and saving as much energy as possible while maintaining a good indoor climate in the building. Kummert et al. (2009) stands as a very good starting point for further investigations on how to build smart heating controller in HVAC systems. Other recent references on building heating include (Nielsen and Madsen, 1995), (Madsen and Holst, 1995), (Andersen et al, 2000), (Jiménez et al, 2008) and (Friling et al, 2009).

Let us now consider a few potential methods:

6.2.5.1. Principal component analysis

As illustrated in this section PCA can by used for, given for instance a mix of temperature sensors, to get a reasonable low pass filtered signal (typically the first principal component and the equivalent time series) and it is also possible very often to detect strange sensors which should then be disregarded or treated accordingly. This is typically the third principal component - or higher.

6.2.5.2. State space models

State space models and related tools like the ordinary Kalman Filter can be used as a multiparameter sensor for states which are not directly measured, as for instance the heat accumulated in the inner concrete or thermal mass of the building. This is very useful for improved control of the heat supply and e.g. for optimized night set back. This kind of state space methods can actually be used in a number of different configurations with different multiparameter sensor values as a result (Madsen, 2007).

6.2.5.3. Linear difference equations

Statistical models formulated as linear difference equations, like the ARMAX models, are very useful for estimating the time constants of the building. These time constants could then be used for an optimal setting of the night-set-back system of the building for instance. The time constants also give a clear picture of the dynamical properties of the building. If the largest time constant is rather high it indicates excellent capabilities for passive storage of heat, including solar input in buildings with a lot of glass. The lowest time constants are those needed for optimizing the heat supply to the building (Jiménez et al, 2008a).

6.2.5.4. UA and gA values

UA (heat loss coefficient) and gA (solar energy to the building) values are probably the most interesting single parameters for a building. These parameters can be estimated using a method developed in a recent project financed by the Electricity Saving Thrust, and implemented in software by ENFOR A/S (Nielsen, 2008).

The methods are based on a low pass filtering of the values for the heat consumption and the climate variables, and then non-parametric regression is used to identify the UA and gA values for the building.

6.2.5.5. Decomposing of variations

This is just another very useful use of state space models and Kalman filter techniques. The idea is to write down a so called decomposed model where the seasonal part and the trend part are separated (for instance), and then the Kalman Filter can be used to estimated a multiparameter signal for the trend and a separate signal for the seasonal (e.g. diurnal) part of the variation in the signal. This is often very useful for optimized control.

6.2.5.6. Low-pass and/or high-pass filtering

This is simply a huge number of approaches where e.g. Finite Impulse Response models are used to filter a multivariate signal into either a low or high pass version of the signals. A low-pass filter passes low-frequency signals but attenuates (reduces the amplitude of) signals with frequencies higher than the cutoff frequency. It provides a smoother form of a signal which is cleared of its short-term oscillations, revealing its long-term trend. It is the opposite for a high pass filter. The filtered signals could be used for an improved control and for detecting non-typical behavior in the signals.

6.2.5.7. Spectrum analysis

By analyzing data in the frequency domain, and for instance by calculating the power spectrum for important variables like measurements of the indoor air temperature, it will be possible to identify sensors with a non-typical diurnal cycle, and this may lead to an identification of non-wanted behaviors of the heating system.

6.2.5.8. Predictive regulators

Most HVAC systems contain time delays. Furthermore these time delays are time varying and only partly know. Classical controllers, like PID and LQG controllers, are not able to deal with such systems, but due to the lack of alternatives, such controllers are often used anyhow.

However, during the past decade new so-called extended generalized predictive controllers have been developed at DTU Informatics, which facilitates new methods for optimal control of stochastic systems containing unknown and time-varying time delays like HVAC systems.

Such controllers are well suited for utilizing information from multi-parameter sensors like those developed during this project.

6.3. Conclusions

The goal of this chapter was to show that statistical methods could be suitable for generating multiparameter sensors. For that purpose, it is very important to work with high quality data. However, preliminary investigations on the data revealed important gaps and a lack of variability in the data due to the limited accuracy of the BMS sensors. Although it cannot be directly demonstrated, we do think that it somehow affected the outcomes of the multivariate analysis.

Even though, other methods could have been applied in the framework of the Multiparameter controller project, a robust approach based on Principal Component Analysis was used and demonstrated its ability to generate a few multiparameter sensors on a simple test case. The response of the building to ambient temperature fluctuations was estimated along with other multiparameter sensors associated to extreme behaviors of certain rooms. However, with further information on each room, a preliminary classification could have been done with respect to the respective functionalities of the rooms (meeting rooms, large open space offices, printer or server rooms, etc) which could help selecting relevant rooms and not the complete set, resulting in an easier interpretation of the results.

For further studies, the use of sensors like the special indoor climate sensors logging the CO_2 concentration, the solar radiation and the relative humidity, could enhance statistical analysis. First, it might be used to validate choices with respect to outlier identification. Then, it could be a great help in estimating the occupancy rate of each room. Finally, it could turn out useful to estimate the sensitivity of each room to solar radiations.

7. Conclusions

The purpose of the project was to investigate how the huge flow of information in traditional BMS systems may be used not only to gain more information on the building and installations but also to control these in a more optimal way.

The available data from the BMS system in a large office building was logged using the original installations plus a few extra sensors. The reason for not adding a larger number of additional sensors was to investigate what could be obtained from a traditional BMS as adding sensors is an extra cost upon the cost of the logging. However in future projects additional sensors should be specified for obtaining more detailed information in specific areas. Especially energy metering on subsystems is important but also eg additional temperature sensors which for instance will make the evaluation of a cooling system more conclusive.

The logged data was transferred by hand. Automatic logging and transfer software should be developed. Software which checks the quality of the data – eg gives an alarm if data is missing, values are hanging or out of range, etc – should also be developed. Prototypes of the latter type of software have been developed as part of the project. General purpose software may be developed based on these prototypes.

One of the aims of the work was to investigate if the availability of detailed logged data from a BMS system would enhance the outcome of a traditional inspection of the building and installations. The logged data were already available as instantaneous values on the different BMS screens. On a screen it is however difficult to compare values displayed on different BMS screens and the historic of the values is lost. The facility management does not have the time to look continuously at the values and to compare the values shown on the BMS screens. Further no time series of data are available. This is even more true during periods without people (including the facility management) in the building.

The project showed that much interesting and valuable information on the building and installations can be obtained which normally would not be obtainable. When looking at time series it is possible to investigate the transient behaviour of the different subsystems and the interactions between the subsystems. In this way faults and inappropriate function of the systems may be detected – in the investigated building: fresh air is often heated first and then cooled, night cooling is not sufficiently utilized, the ventilation systems starts too early (and not at the same hour) and stop too late, etc. – all things which are very difficult/impossible to detect when just looking at the instantaneous values on the BMS screen.

Based on the visual inspection of the time series from the case building it has been estimated that it is possible save 50% on the electricity consumption equal to around 350 MWh/year and 25% on the consumption of district heating equal to around 300 MWh/year. Based on the findings from the visual inspection a strategy for obtaining the estimated energy savings has been worked out and will be implemented during the first half year of 2010.

The results from the visual inspection relate specifically to the investigated building and cannot directly be transferred to other buildings as the installations and control may differ considerably from the here investigated building. However, it is judge that the result from the project may act as a source of inspiration for finding fault and inappropriate functions in other buildings which may lead to considerably energy savings. But the energy saving potential will be increased if time series from the BMS are logged and analysed.

It is, however, very time consuming to investigate thousands of time series by eye and also very expensive as the work should be done by experts. Prototypes of software for an automatically check of the main parameters have been developed in the programme R. And also software which in a condensed and easy readable form presents the actual condition of the building and installations for the facility management so that they may react appropriately. Cumulated frequency curves and box plots are such tools. However, the prototype software need further development in order to become general purpose software which may be implemented at different platforms.

However, in order to obtain an optimal control of these types of buildings there is a need for online optimization. Multiparameter controllers based on multiparameter sensors are believed to be able to automatically optimize the indoor climate while minimizing the energy demand. Initial investigations concerning generation of multiparameter sensors have been carried out in the project. Especially Principal Component Parameters (PCA) were investigated. These were as cumulative frequency curves and box plots used to investigate the air temperatures in the offices. But where cumulative frequency curves and box plots need an evaluation and action from a human, PCAs may be utilized in online robust controls. However, much work and development are still needed in order to create general purpose multiparameter sensors which easily may be integrated in BMS systems as multiparameter controllers for online optimization of the indoor climate and energy demand in buildings.

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Appendixes

Appendix 1

SQL scripts

```
-- ----------------------------------------------------------------------------
-- DIMENSION TABLES
-- ----------------------------------------------------------------------------

DROP TABLE IF EXISTS `bldg_th1`.`d_maalepunkt`;
CREATE TABLE  `bldg_th1`.`d_maalepunkt` (
  `id_maalepunkt` int(11) NOT NULL auto_increment,
  `maalepunkt_navn` varchar(50) NOT NULL,
  `anlaeg` varchar(10) default NULL,
  `anlaeg_besk` varchar(100) default NULL,
  `maalepunkt` varchar(50) default NULL,
  `maalepunkt_besk` varchar(100) default NULL,
  `enhed` varchar(25) default NULL,
  `SET_MAAL` varchar(4) default NULL,
  `rumzone` varchar(10) default NULL,
  `zonenr` smallint(5) unsigned default NULL,
  `delbygning` varchar(10) default NULL,
  `etage` tinyint(3) default NULL,
  `facadeplacering` char(1) default NULL,
  `retning` varchar(2) default NULL,
  `areal` decimal(3,1) default NULL,
  `sort` smallint(5) unsigned default NULL,
  PRIMARY KEY  (`id_maalepunkt`),
  KEY `ix_maalepunkt_navn` (`maalepunkt_navn`)
) ENGINE=MyISAM AUTO_INCREMENT=1056 DEFAULT CHARSET=latin1;



DROP TABLE IF EXISTS `bldg_th1`.`d_period_day`;
CREATE TABLE  `bldg_th1`.`d_period_day` (
  `id_period` smallint(5) unsigned NOT NULL auto_increment COMMENT
'Surrogate key',
  `id_period2` int(10) unsigned NOT NULL default '0' COMMENT 'Date-like
key',
  `year` smallint(5) unsigned default '0',
  `quarter` tinyint(3) unsigned default '0',
  `month` tinyint(3) unsigned default '0',
  `day` tinyint(3) unsigned default '0',
  `date` date default '0000-00-00',
  `week` tinyint(3) unsigned default '0',
  `week_0_53` tinyint(3) unsigned default '0',
  `yearmonth` varchar(7) default NULL,
  `year_week` varchar(7) default '',
  `month_name_en` varchar(9) default '',
  `day_name_en` varchar(9) default '',
  `month_name_da` varchar(9) default '',
  `day_name_da` varchar(7) default '',
  `last_day` date default '0000-00-00',
  `last_day_fl` tinyint(1) default '0',
  `days_in_month` smallint(5) unsigned default '0',
  `day_of_week_en` tinyint(3) unsigned default NULL,
  `day_of_week_da` tinyint(3) unsigned default NULL,
  PRIMARY KEY  (`id_period`),
```

```
  UNIQUE KEY `IX_ID_PERIOD2` (`id_period2`)
) ENGINE=MyISAM AUTO_INCREMENT=733 DEFAULT CHARSET=latin1 COMMENT='Period
dimension - day';


DROP TABLE IF EXISTS `bldg_th1`.`d_period_rel_5min`;
CREATE TABLE  `bldg_th1`.`d_period_rel_5min` (
  `id_klok` int(11) default NULL,
  `klok` char(6) default NULL,
  `time` char(6) default NULL,
  `heltime` tinyint(4) default NULL,
  `dt_ins` datetime default NULL
) ENGINE=MyISAM DEFAULT CHARSET=latin1;


-- ------------------------------------------------------------------------
-- EXTRACT TABLES
-- ------------------------------------------------------------------------

DROP TABLE IF EXISTS `bldg_th1`.`extract_ik_log`;
CREATE TABLE  `bldg_th1`.`extract_ik_log` (
  `maalepunkt_navn` varchar(15) default NULL,
  `id_dato` int(11) default NULL,
  `id_klok` int(11) default NULL,
  `temp` decimal(10,3) default NULL,
  `rh` decimal(10,3) default NULL,
  `light` decimal(10,3) default NULL,
  `co2` decimal(10,3) default NULL,
  KEY `maalepunkt_navn` (`maalepunkt_navn`,`id_dato`,`id_klok`)
) ENGINE=MyISAM DEFAULT CHARSET=latin1;

DROP TABLE IF EXISTS `bldg_th1`.`extract_tac`;
CREATE TABLE  `bldg_th1`.`extract_tac` (
  `anl_alt` varchar(10) default NULL,
  `maalepunkt_navn` varchar(50) default NULL,
  `tidspunkt_str` char(19) default NULL,
  `tidspunkt` datetime default NULL,
  `vaerdi` decimal(10,2) default NULL,
  `extract_time` datetime default NULL,
  KEY `maalepunkt_navn` (`maalepunkt_navn`,`tidspunkt`,`vaerdi`)
) ENGINE=MyISAM DEFAULT CHARSET=latin1;

DROP TABLE IF EXISTS `bldg_th1`.`fct_dong`;
CREATE TABLE  `bldg_th1`.`fct_dong` (
  `id_maalepunkt` int(11) NOT NULL,
  `id_dato` int(11) NOT NULL,
  `id_klok` int(11) NOT NULL,
  `maalepunkt_navn` varchar(50) NOT NULL,
  `vaerdi` decimal(8,2) default NULL,
  `dt_ins` timestamp NOT NULL default CURRENT_TIMESTAMP on update CUR-
RENT_TIMESTAMP,
  PRIMARY KEY  (`maalepunkt_navn`,`id_dato`,`id_klok`),
  KEY `ix_maalepunkt_navn` (`maalepunkt_navn`),
  KEY `ix_id_dato` USING BTREE (`id_dato`)
) ENGINE=MyISAM DEFAULT CHARSET=latin1;


-- ------------------------------------------------------------------------
```

```sql
-- FACT TABLES
-- ---------------------------------------------------------------------------

DROP TABLE IF EXISTS `bldg_th1`.`fct_ik_log`;
CREATE TABLE  `bldg_th1`.`fct_ik_log` (
  `id_maalepunkt` int(11) default NULL,
  `id_dato` int(11) default NULL,
  `id_klok` int(11) default NULL,
  `maalepunkt_navn` varchar(20) default NULL,
  `vaerdi` decimal(10,3) default NULL,
  KEY `maalepunkt_navn` (`maalepunkt_navn`,`id_dato`,`id_klok`)
) ENGINE=MyISAM DEFAULT CHARSET=latin1;


DROP TABLE IF EXISTS `bldg_th1`.`fct_tac`;
CREATE TABLE  `bldg_th1`.`fct_tac` (
  `id_maalepunkt` int(11) NOT NULL,
  `id_dato` int(11) NOT NULL,
  `id_klok` int(11) NOT NULL,
  `maalepunkt_navn` varchar(50) NOT NULL,
  `vaerdi` decimal(8,2) default NULL,
  `dt_ins` timestamp NOT NULL default CURRENT_TIMESTAMP on update CUR-
RENT_TIMESTAMP,
  PRIMARY KEY  (`maalepunkt_navn`,`id_dato`,`id_klok`),
  KEY `ix_maalepunkt_navn` (`maalepunkt_navn`),
  KEY `ix_id_dato` USING BTREE (`id_dato`),
  KEY `ix_id_maalepunkt` USING BTREE (`id_maalepunkt`)
) ENGINE=MyISAM DEFAULT CHARSET=latin1;


-- ---------------------------------------------------------------------------
-- REPORTING VIEW
-- ---------------------------------------------------------------------------

DROP VIEW IF EXISTS `bldg_th1`.`v_report_tac`;
CREATE ALGORITHM=UNDEFINED DEFINER=`root`@`localhost` SQL SECURITY DEFINER
VIEW  `bldg_th1`.`v_report_tac`
AS
select `f`.`id_maalepunkt` AS `id_maalepunkt`,
`f`.`id_dato` AS `id_dato`,
`f`.`id_klok` AS `id_klok`,
`f`.`maalepunkt_navn` AS `maalepunkt_navn`,
`f`.`vaerdi` AS `vaerdi`,
`dm`.`anlaeg` AS `anlaeg`,
`dm`.`anlaeg_besk` AS `anlaeg_besk`,
`dm`.`maalepunkt` AS `maalepunkt`,
`dm`.`maalepunkt_besk` AS `maalepunkt_besk`,
`dm`.`enhed` AS `enhed`,
`dm`.`SET_MAAL` AS `SET_MAAL`,
`dm`.`rumzone` AS `rumzone`,
`dm`.`zonenr` AS `zonenr`,
`dm`.`delbygning` AS `delbygning`,
`dm`.`etage` AS `etage`,
`dm`.`facadeplacering` AS `facadeplacering`,
`dm`.`retning` AS `retning`,
`dm`.`areal` AS `areal`,
`dm`.`sort` AS `sort`,
```

```
`dp`.`year` AS `year`,
`dp`.`quarter` AS `quarter`,
`dp`.`month` AS `month`,
`dp`.`day` AS `day`,
`dp`.`week` AS `week`,
`dp`.`week_0_53` AS `week_0_53`,
`dp`.`yearmonth` AS `yearmonth`,
`dp`.`year_week` AS `year_week`,
`dp`.`month_name_en` AS `month_name_en`,
`dp`.`day_name_en` AS `day_name_en`,
`dp`.`month_name_da` AS `month_name_da`,
`dp`.`day_name_da` AS `day_name_da`,
`dp`.`last_day` AS `last_day`,
`dp`.`last_day_fl` AS `last_day_fl`,
`dp`.`days_in_month` AS `days_in_month`,
`dp`.`day_of_week_en` AS `day_of_week_en`,
`dp`.`day_of_week_da` AS `day_of_week_da`,
`dk`.`klok` AS `klok`,
`dk`.`time` AS `time`,
`dk`.`heltime` AS `heltime`
from (((`fct_tac` `f`
   join `d_maalepunkt` `dm`
     on((`f`.`maalepunkt_navn` = `dm`.`maalepunkt_navn`)))
   join `d_period_day` `dp`
     on((`f`.`id_dato` = `dp`.`id_period2`)))
   join `d_period_rel_5min` `dk`
     on((`f`.`id_klok` = `dk`.`id_klok`)));



-- ---------------------------------------------------------------------------
-- STORED PROCEDURE (populating d_period_day)
-- ---------------------------------------------------------------------------

CREATE DEFINER=`root`@`localhost` PROCEDURE
`bldg_th1`.`sp_pop_d_period_day`(
    start_date                  DATETIME
   ,end_date                    DATETIME
   ,p_user                      VARCHAR(25)
   ,OUT p_sqlcode               INT
   ,OUT p_status_message        VARCHAR(100))
BEGIN

SET @date_v = start_date;

REPEAT

   INSERT INTO `bldg`.`d_period_day` VALUES (
    null,
    concat(cast(year(@date_v) as char),
           lpad(cast(month(@date_v) as char),2,'0'),
           lpad(cast(day(@date_v) as char),2,'0')),
    year(@date_v),
    quarter(@date_v),
    month(@date_v),
    day(@date_v),
    @date_v,
    week(@date_v,3),
```

```
    week(@date_v,1),
    concat(year(@date_v),'-',lpad(cast(MONTH(@date_v) as char),2,'0')),
    concat(year(@date_v),'-',lpad(cast(week(@date_v,3) as char),2,'0')),
    monthname(@date_v),
    dayname(@date_v),
    case monthname(@date_v)
         when 'January' then 'Januar'
         when 'February' then 'Februar'
         when 'March' then 'Marts'
         when 'April' then 'April'
         when 'May' then 'Maj'
         when 'June' then 'Juni'
         when 'July' then 'Juli'
         when 'August' then 'August'
         when 'September' then 'September'
         when 'October' then 'Oktober'
         when 'November' then 'November'
         when 'December' then 'December'
    end,
    case dayname(@date_v)
         when 'Monday' then 'Mandag'
         when 'Tuesday' then 'Tirsdag'
         when 'Wednesday' then 'Onsdag'
         when 'Thursday' then 'Torsdag'
         when 'Friday' then 'Fredag'
         when 'Saturday' then 'Lørdag'
         when 'Sunday' then 'Søndag'
    end,
    last_day(@date_v),
    last_day(@date_v)=date,
    day(last_day(@date_v)),
    weekday(@date_v)+1,
    dayofweek(@date_v));

    SET @date_v = DATE_ADD(@date_v,INTERVAL 1 day);

UNTIL @date_v > end_date

END REPEAT;

SET p_sqlcode=0;
SET p_status_message='aaa';

END


-- ------------------------------------------------------------------------
-- DECODE TIMESERIES NAMES
-- ------------------------------------------------------------------------

-- ------------------------------------------------------------------------
--  Create VIEW: Time series ID's in source (SELECT DISTINCT)
-- ------------------------------------------------------------------------
CREATE OR REPLACE VIEW `bldg_th1`.`v_tac_maalepunkt_navn_distinct`
(maalepunkt_navn)
AS
SELECT DISTINCT `extract_tac`.`maalepunkt_navn` AS `maalepunkt_navn`
FROM `bldg_th1`.`extract_tac`;
```

```
-- ----------------------------------------------------------------------------
--  Create VIEW: Decode time series ID's
-- ----------------------------------------------------------------------------
CREATE OR REPLACE VIEW `bldg_th1`.`v_tac_maalepunkt_navn_decode`
(maalepunkt_navn,lokation,bygning,etage,anlaeg,rumzone,maalepunkt)
AS
SELECT maalepunkt_navn,
SUBSTRING_INDEX(maalepunkt_navn,'-',1),
SUBSTR(maalepunkt_navn,INSTR(maalepunkt_navn,'-')+1,2),
SUBSTR(maalepunkt_navn,INSTR(maalepunkt_navn,'-')+3,2),
SUBSTRING_INDEX(SUBSTRING_INDEX(maalepunkt_navn,'-',3),'-',-1),
CASE WHEN INSTR(SUBSTRING_INDEX(SUBSTRING_INDEX(maalepunkt_navn,'-',4),'-
',-1),'IRR')>0
     THEN INSTR(SUBSTRING_INDEX(SUBSTRING_INDEX(maalepunkt_navn,'-',4),'-
',-1),'IRR')
     ELSE '-' END,
TRIM(TRAILING '_LOG_X' FROM SUBSTRING_INDEX(maalepunkt_navn,'-',-1))
FROM `bldg_th1`.`v_tac_maalepunkt_navn_distinct`;
```

```
-- ----------------------------------------------------------------------------
-- extract_tac_logfil
-- ----------------------------------------------------------------------------


LOAD DATA INFILE '@PATH/tac_log.txt'
IGNORE INTO TABLE `bldg_th1`.`fct_tac`
FIELDS TERMINATED BY '\t' LINES TERMINATED BY '\r\n'
(@anl_alt,@maalepunkt_navn,@tidspunkt,@vaerdi)
SET `maalepunkt_navn` = @maalepunkt_navn,
    `id_dato` = CAST(
        CONCAT(substring(@tidspunkt,7,4),
               substring(@tidspunkt,4,2),
               substring(@tidspunkt,1,2))
                AS UNSIGNED INTEGER),
    `id_klok` = CAST(
        CONCAT(substring(@tidspunkt,12,2),
               substring(@tidspunkt,15,1),
               case when CAST(substring(@tidspunkt,16,1)
                         AS UNSIGNED INTEGER)<5
                    then '0'
                    else '5'
               end,'00')
                AS UNSIGNED INTEGER),
    `vaerdi` = 0 + @vaerdi;
```

Appendix 2.1 Monthly aggregated temperatures at each measurement location

Logger	Month	Mean	Median	Var	Std	Min	Max
3028	3	24.2	24.2	0.1	0.4	23	25.1
	4	24.3	24.2	0.1	0.3	23.3	26
	5	24.1	24	0.4	0.6	22.6	25.8
	6	25.3	25.2	0.7	0.9	23.7	27.3
	7	26.1	25.9	1.4	1.2	23.9	29.1
	8	26.3	26.2	0.5	0.7	24.5	28.2
	9	25.8	25.8	0.6	0.8	23.3	27.7
	10	24.9	24.8	0.8	0.9	22.8	27.2
3029	2	23.5	23.5	0.1	0.3	22.6	24.4
	3	23.6	23.7	0.2	0.4	22.4	24.5
	4	24.2	24.3	0.2	0.4	22.8	25.3
	5	23.9	24	0.3	0.6	22.4	24.9
	6	24.6	24.7	0.4	0.6	23.1	26.2
	7	24.5	24.5	0.5	0.7	22.7	26.4
	8	24.1	24.1	0.2	0.5	22.5	25.8
	9	23.5	23.5	0.2	0.5	21.9	24.7
	10	23.4	23.4	0.1	0.4	22.4	24.3
3033	2	24.4	24.5	0.1	0.4	23.2	25.8
	3	24.4	24.5	0.5	0.7	22.1	26.1
	4	24.6	24.6	0.3	0.5	23	26
	5	24.6	24.8	0.6	0.8	22.3	26.1
	6	25.5	25.5	0.6	0.8	23.9	27.5
	7	24.7	24.6	0.5	0.7	23.2	26.7
	8	24.2	24.2	0.2	0.4	23	25.6
	9	24.6	24.6	0.2	0.5	23.2	25.6
	10	24.6	24.6	0.1	0.3	23.4	25.4
3034	2	24	24	0.2	0.4	22.5	25.2
	3	24.6	24.7	0.4	0.6	22.8	25.9
	4	24.9	24.9	0.3	0.6	23.2	26.9
	5	24.7	24.9	0.8	0.9	22.2	26.2
	6	25.6	26	1.3	1.1	23.6	27.4
	7	25	25	0.3	0.5	23.7	26.8
	8	24.9	24.9	0.2	0.5	23.5	26.1
	9	24.3	24.3	0.1	0.4	23.3	25.2
	10	24.2	24.2	0	0.2	23.6	24.8

Logger	Month	Mean	Median	Var	Std	Min	Max
3041	2	24.8	24.8	0.5	0.7	23.2	26.5
	3	24.1	24	1.1	1	21.6	26.4
	4	24.7	24.8	0.8	0.9	21.9	26.3
	5	23.6	23.4	1.4	1.2	21.7	26.6
	6	24.7	24.6	1.7	1.3	22.5	27.7
	7	25.1	25	1.5	1.2	22.5	27.9
	8	24.4	24.4	1.2	1.1	22.2	27.3
	9	24.9	24.9	1.3	1.2	22.4	27.7
	10	24.7	24.7	0.8	0.9	22.3	27.1
3031	2	24.3	24.3	0.7	0.8	20.5	27.4
	3	24	24.1	1.1	1	21.1	26.6
	4	24.8	24.8	1.2	1.1	22	28.8
	5	24.5	24.5	1.5	1.2	20.5	27.2
	6	25.9	26	1.9	1.4	22.9	29.5
	7	25.2	25	2	1.4	22.3	29.8
	8	24.6	24.5	0.9	0.9	22.4	27.3
	9	24.5	24.4	0.6	0.8	22.6	27.1
	10	24	23.9	0.6	0.8	19.4	26.1
3036	2	23.3	23.3	0.1	0.4	21.6	24.3
	3	23.5	23.6	0.2	0.5	22.3	24.3
	4	24.3	24.4	0.2	0.4	22.7	25.3
	5	23.5	23.7	0.2	0.5	22.2	24.5
	6	24.5	24.6	0.3	0.5	23.4	25.9
	9	22.6	22.5	0.1	0.4	21.6	23.9
	10	22.6	22.6	0.1	0.3	21.8	23.2
3037	2	23.7	23.7	0.1	0.4	21.7	24.6
	3	23.7	23.8	0.3	0.5	22.3	24.5
	4	24.6	24.7	0.1	0.4	23.1	25.3
	5	23.7	23.6	0.2	0.5	22.1	24.8
	6	24.1	24.2	0.4	0.6	22.7	25.5
	7	24.3	24.2	0.4	0.6	22.9	25.9
	8	24.2	24.2	0.4	0.6	22.1	25.5
	9	23	22.9	0.2	0.4	21.9	24.4
	10	22.9	22.9	0	0.1	22.6	23.3

Logger	Month	Mean	Median	Var	Std	Min	Max
3038	2	23.7	23.8	0.1	0.3	22.4	24.3
	3	23.6	23.7	0.2	0.4	22.6	24.4
	4	24.1	24.2	0.2	0.4	22.7	25.1
	5	23.5	23.5	0.3	0.5	21.7	24.6
	6	24.4	24.2	0.4	0.6	23.3	26
	7	23.9	24.2	0.8	0.9	22	25.5
	8	23.7	23.7	0.3	0.5	22.3	25.1
	9	23.2	23.2	0.1	0.3	22.2	24.1
	10	22.8	22.8	0.2	0.4	21.4	23.8
3039	2	24.1	24.1	0.1	0.3	22.3	24.9
	3	24	24	0.2	0.4	23	24.8
	4	24.9	24.9	0.3	0.5	23.7	26.2
	5	24.4	24.5	0.3	0.6	22.7	25.4
	6	25.3	25.1	0.9	1	23.6	27
	7	24.7	24.8	0.6	0.8	23.4	26.4
	8	24.2	24.2	0.4	0.7	23	26.3
	9	23.8	23.8	0.3	0.5	22.7	24.8
	10	23.6	23.6	0.2	0.4	22.3	24.6
3040	2	23.7	23.7	0.1	0.3	20.2	24.5
	3	23.7	23.8	0.2	0.5	22.6	24.9
	4	24.9	24.9	0.3	0.5	23.2	25.9
	5	23.8	23.7	0.3	0.6	22.5	25.7
	6	24.8	24.8	0.3	0.6	23.7	25.7
	9	24.6	24.7	0.2	0.4	23.4	25.3
	10	24.5	24.6	0.2	0.5	23.2	25.5
3042	2	24	24	0.2	0.5	22.2	25.5
	3	23.8	23.9	0.3	0.6	22.3	25.1
	4	24.2	24.3	0.3	0.6	22.4	25.3
	5	24	24.1	0.5	0.7	22.1	25.2
	6	24.5	24.4	0.5	0.7	23.1	26.1
	7	24.2	24.1	0.8	0.9	22.2	26
	8	24.1	24.1	0.5	0.7	22	25.7
	9	23.8	23.9	0.4	0.6	22.4	25
	10	23.6	23.7	0.3	0.5	22.3	24.7
3046	2	23.2	23	0.3	0.6	21.4	25.3
	3	23.4	23.4	0.7	0.8	21.3	25.3
	4	25.1	25.2	0.8	0.9	22.4	27.1
	5	24.3	24.4	0.8	0.9	21.7	26.5
	6	26	26	0.3	0.5	24.8	27.2
	9	24.7	24.5	1.1	1	22.7	27.1
	10	23.9	23.7	0.9	1	20.5	28.4

Appendix 2.2 Monthly aggregated relative air humidity at each measurement location

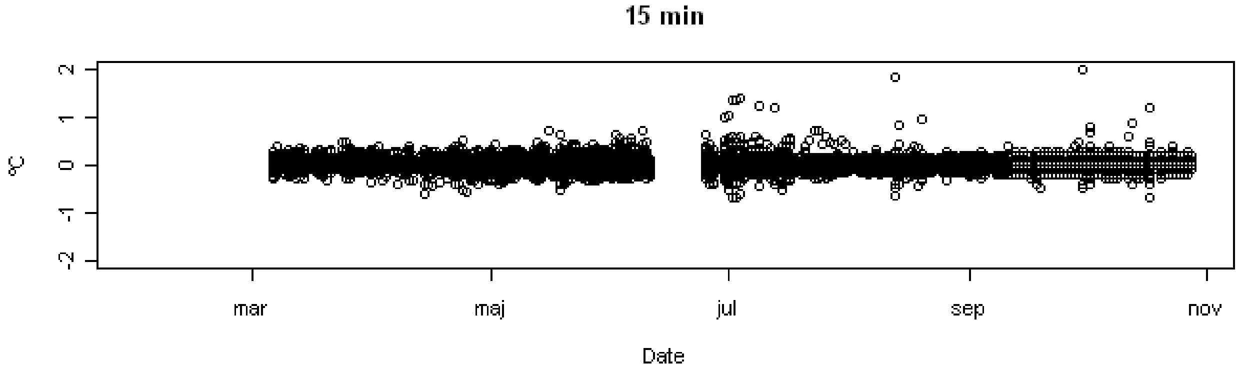
Logger	month	mean	median	var	std	min	max
3028	3	22.3	21.4	18.5	4.3	15.3	29.9
	4	25.8	25.9	10.1	3.2	19.9	34.3
	5	31.1	31.5	19.1	4.4	21.2	41.8
	6	36.8	36.8	8.3	2.9	30.6	42.4
	7	39.9	40.1	12	3.5	32.9	51.9
	8	44.8	44	20.5	4.5	33.2	54.4
	9	37.2	37.1	28.4	5.3	27.1	49.2
	10	34.3	33.8	8.4	2.9	28.6	42.2
3029	2	26.5	27.2	12.2	3.5	14.9	32.2
	3	23	22	17.2	4.1	15.8	29.9
	4	26.3	26.6	9.2	3	20.5	34.7
	5	31.4	31.9	18.3	4.3	22.3	39.4
	6	37.9	37	7.9	2.8	31.4	43.7
	7	43.9	43.2	13.7	3.7	37.3	55.8
	8	50.4	49.7	16.8	4.1	40.5	59.3
	9	43.1	42.6	34.5	5.9	31.9	56
	10	38.6	38.5	9.4	3.1	32.5	46.2
3033	2	24.3	25.2	12.2	3.5	13.5	29.9
	3	21.3	20.6	16.4	4	14.2	28.6
	4	24.8	24.7	10.5	3.2	19.1	34.1
	5	29.7	29.8	21.4	4.6	19.5	39
	6	35.2	34.9	9.9	3.1	29.4	41.7
	7	42.8	42.1	19.4	4.4	33.9	53.8
	8	49.9	49.1	22.2	4.7	36.8	59
	9	39.7	38	47.2	6.9	28.2	54.5
	10	34.6	34.7	1.3	1.1	32.1	37
3034	2	25.4	26.3	14.7	3.8	13.4	32.1
	3	21.2	20.2	15.1	3.9	14.5	27.9
	4	24.3	24.3	9.6	3.1	18.6	32.6
	5	29.3	29.3	20.8	4.6	20.6	38.6
	6	35.1	34.4	11.7	3.4	28.9	42.7
	7	41.2	40.7	13	3.6	33.7	51.5
	8	47.4	46.4	20.8	4.6	37.3	57.5
	9	39.5	38.1	40.3	6.4	26.5	52.8
	10	34.9	34.6	7.7	2.8	29.4	42.3

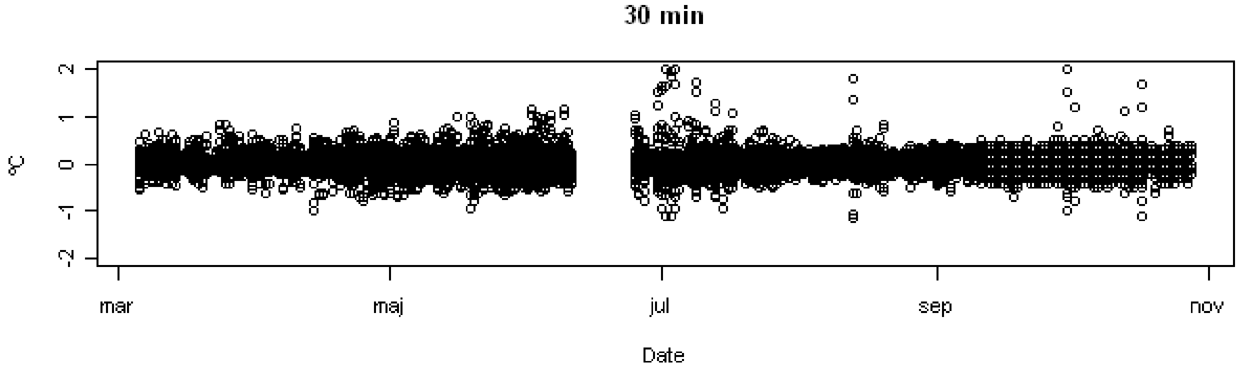
Logger	month	mean	median	var	std	min	max
3041	2	23.9	24.8	12.5	3.5	12.9	30.5
	3	21.4	20.7	15.9	4	13.7	28
	4	24.8	24.1	12.4	3.5	19	35.9
	5	32.4	33	25.1	5	21.3	43.9
	6	38.4	38.4	18	4.2	30.3	48.1
	7	42.7	42.2	22.4	4.7	33	58
	8	49.9	49.5	29.3	5.4	36	61.5
	9	39.3	37.3	55.2	7.4	26.5	57
	10	35.2	34.8	7.4	2.7	30.4	42.6
3031	2	24.7	25.8	16.5	4.1	11.8	33.1
	3	22.1	21.1	19.5	4.4	13.4	30.2
	4	24.7	24.9	12.5	3.5	17.8	34.2
	5	30.1	30.7	25.3	5	17.3	39.4
	6	35.4	35.9	19.4	4.4	26.5	46.4
	7	41.5	40.8	22.7	4.8	29	60.4
	8	49.1	48.4	31.1	5.6	33.8	61.3
	9	39.2	38.5	40.9	6.4	26.9	53.9
	10	36	35.4	10.5	3.2	29.2	46.1
3036	2	24	25	15.1	3.9	11.8	30.5
	3	21.1	20	16.1	4	14	27.6
	4	24.4	24.2	9.4	3.1	19.5	33.1
	5	31.1	31.6	20.2	4.5	22.2	39.9
	6	37.9	37.2	4.3	2.1	32.7	42.8
	9	39.3	39.1	15.3	3.9	31.4	53.6
	10	38.3	37.9	10.3	3.2	31.9	46.6
3037	2	24.2	25	14.3	3.8	12.5	30.5
	3	21.3	20.7	17.1	4.1	14.2	28.6
	4	24.3	24.1	9.9	3.1	18.5	33
	5	31	31.4	18.6	4.3	22.5	40.2
	6	39	37.9	9	3	31.6	45.1
	7	43.8	43.2	16.5	4.1	36.6	54.4
	8	50.5	50	20	4.5	39	60.6
	9	43.7	41.9	50.3	7.1	30.6	59.5
	10	38.1	38.2	6.7	2.6	32.9	44.3

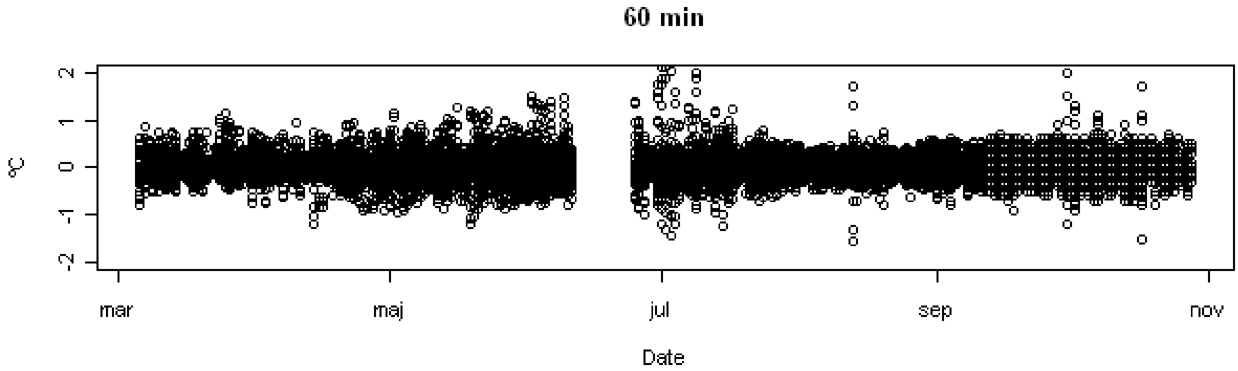
Logger	month	mean	median	var	std	min	max
3038	2	24.6	25.4	13.8	3.7	13.1	30.5
	3	21.8	20.9	17.3	4.2	14.6	28.7
	4	25.3	24.9	11	3.3	19.9	34.8
	5	31.4	31.9	23.9	4.9	20.8	41.8
	6	37.8	37.2	8.5	2.9	30.6	43.4
	7	43.8	43.5	23.4	4.8	33.5	55
	8	50.5	49.9	21.6	4.6	40.1	60.3
	9	42.4	42.1	37	6.1	30.4	55.3
	10	39.3	38.9	9.3	3.1	33.9	47
3039	2	23.7	24.5	12.9	3.6	13.4	29.1
	3	21	20.1	15.9	4	14.4	28
	4	23.6	23.6	9.3	3.1	18.8	32.5
	5	29	29.3	19.5	4.4	20.2	37
	6	35.4	34.7	7.7	2.8	28.5	41.2
	7	41.4	40.6	14.5	3.8	35.1	51.2
	8	48.7	47.8	21.8	4.7	38	59.1
	9	39.9	39.3	43.8	6.6	28.1	54.1
	10	35.6	35.4	9.3	3.1	29.5	44
3040	2	24.7	25.5	15.9	4	12.8	31.8
	3	21.5	20.5	18.8	4.3	14.1	29.1
	4	23.8	23.8	10.4	3.2	18.2	32.6
	5	29.7	30.6	23	4.8	19.3	39.4
	6	36.3	35.9	6.2	2.5	31.5	42.5
	9	34.1	33.9	16.4	4.1	25.4	47.1
	10	33.8	33.5	9.7	3.1	28	42
3042	2	25	26	14.6	3.8	13.4	31.6
	3	22.4	21.9	17.1	4.1	15.3	29.6
	4	25.9	25.9	11.4	3.4	19.9	35.4
	5	31	31.6	24.6	5	19.7	41
	6	38	37.6	9.2	3	31.4	44.6
	7	44	43.7	20.4	4.5	35.9	55.6
	8	49.9	49	22.3	4.7	36.7	59.9
	9	41.7	40.5	48.3	7	29.8	57.7
	10	37.9	37.5	9.6	3.1	31.6	45.9
3046	2	26	27	18.8	4.3	13	33.5
	3	22.3	21.5	21.7	4.7	14.4	30.3
	4	24.3	24.8	14.4	3.8	17.4	34.5
	5	30.3	30.5	21.5	4.6	20.7	39.6
	6	34.7	33.7	7	2.6	30.8	40.6
	9	35.3	35.2	19.3	4.4	27.2	49.6
	10	36.9	36.4	11.5	3.4	28.5	45.7

Appendix 2.3 Temporal temperature difference based on 15 min, 30 min and 60 min time lags

3028







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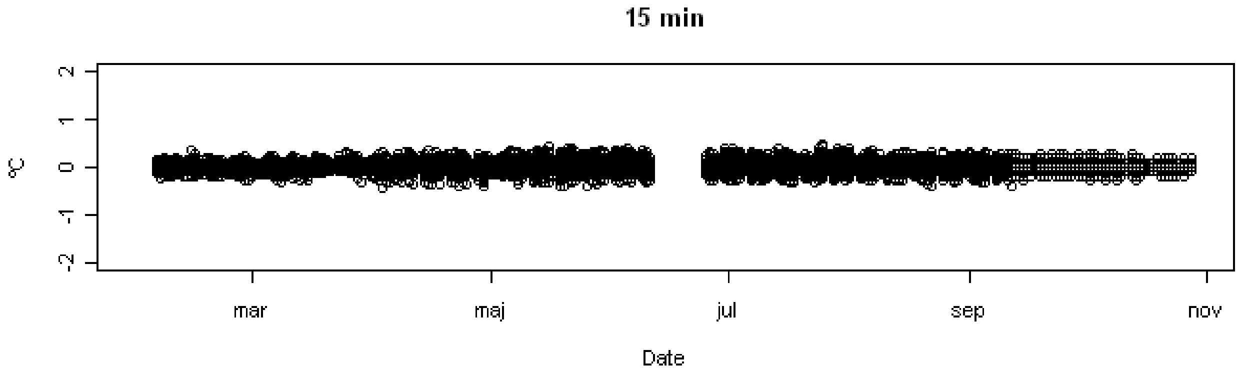

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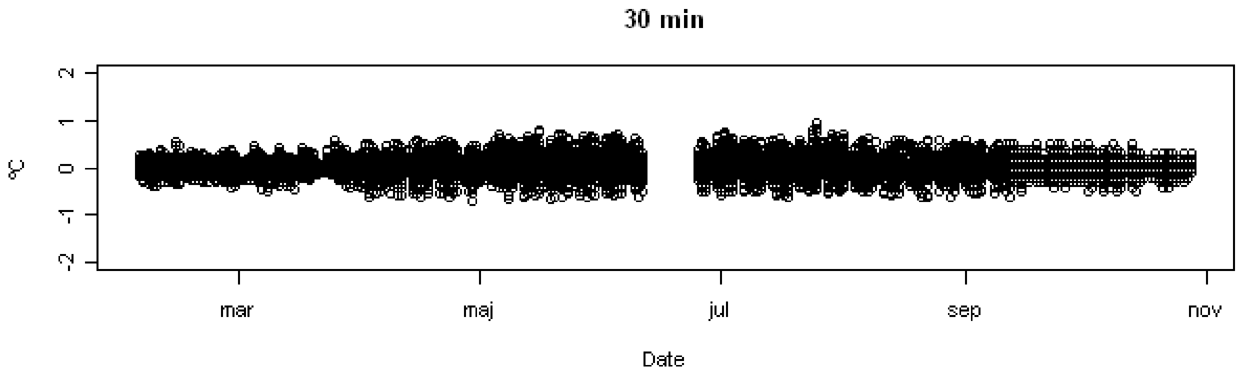

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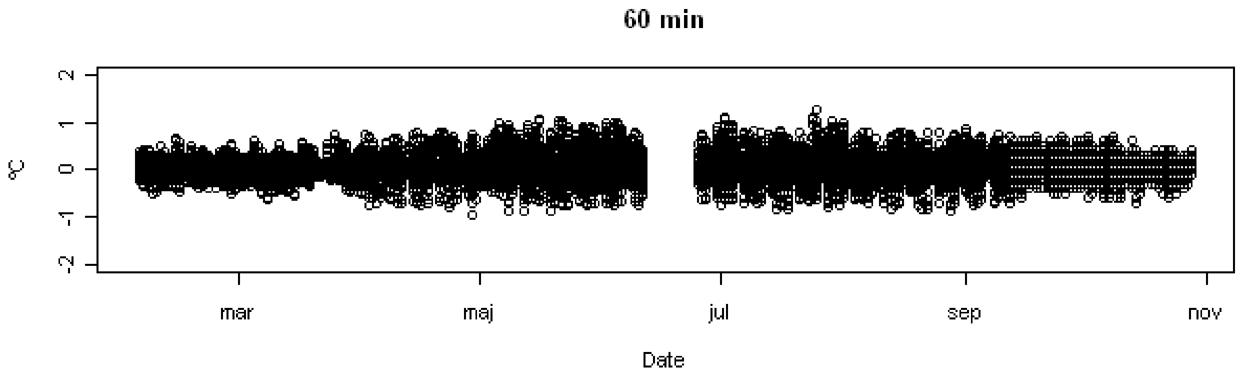

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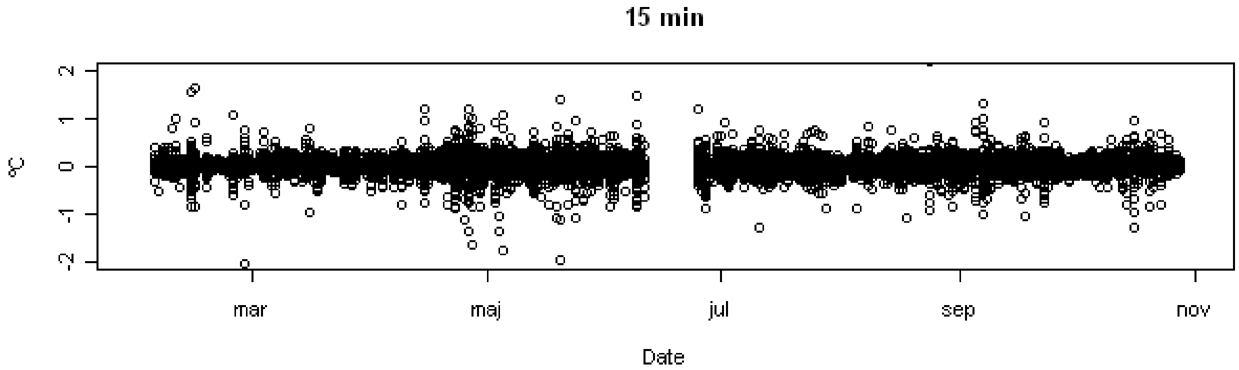
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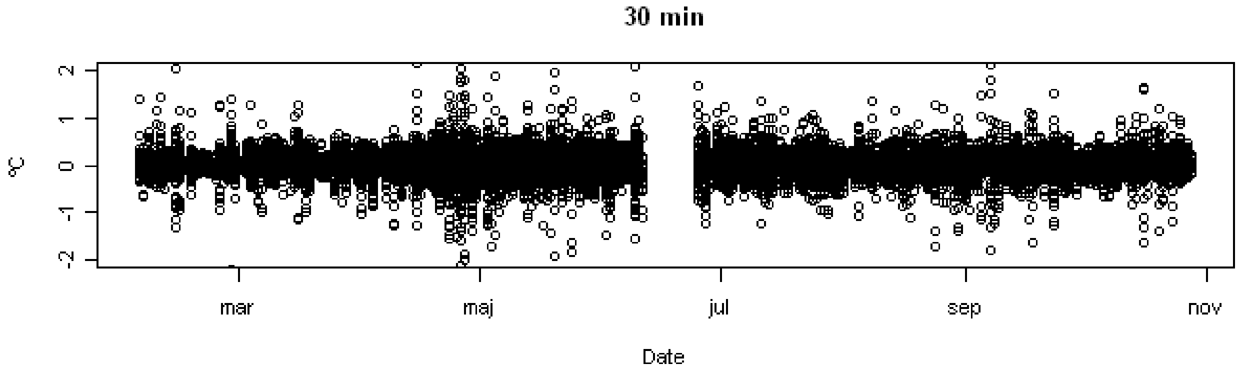
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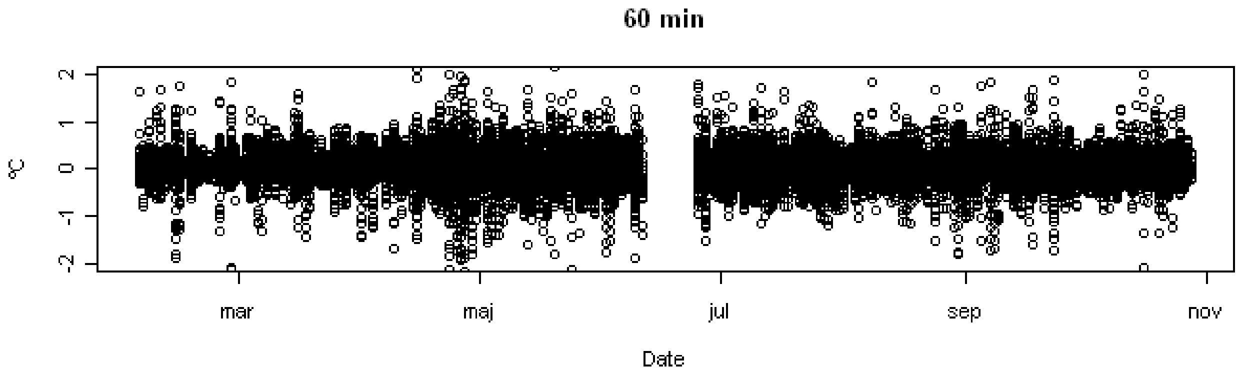
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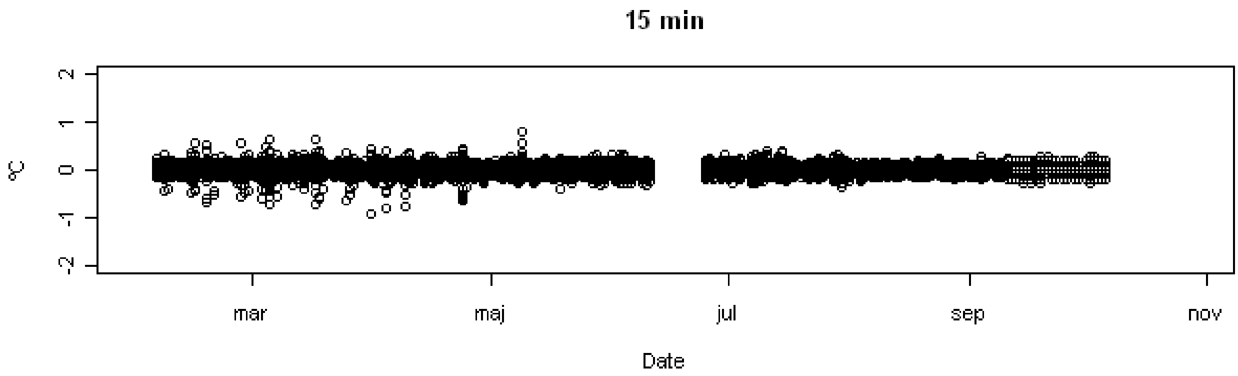
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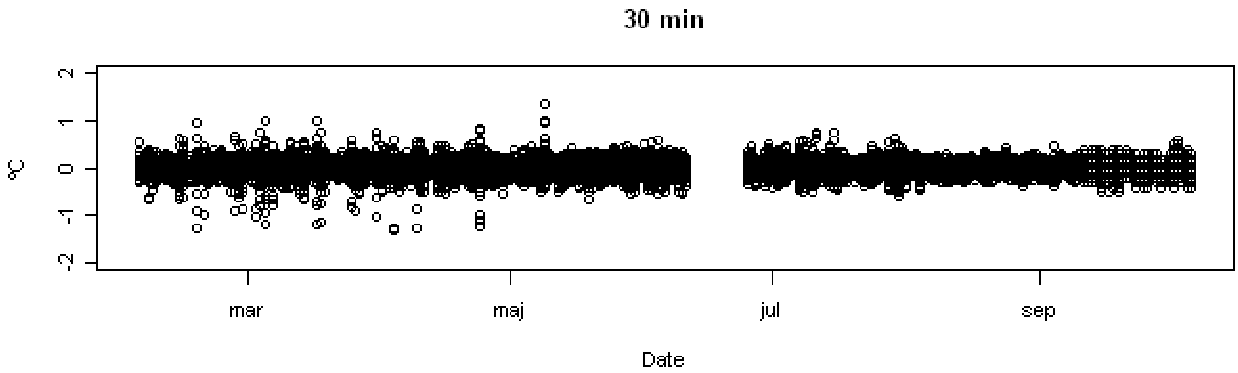
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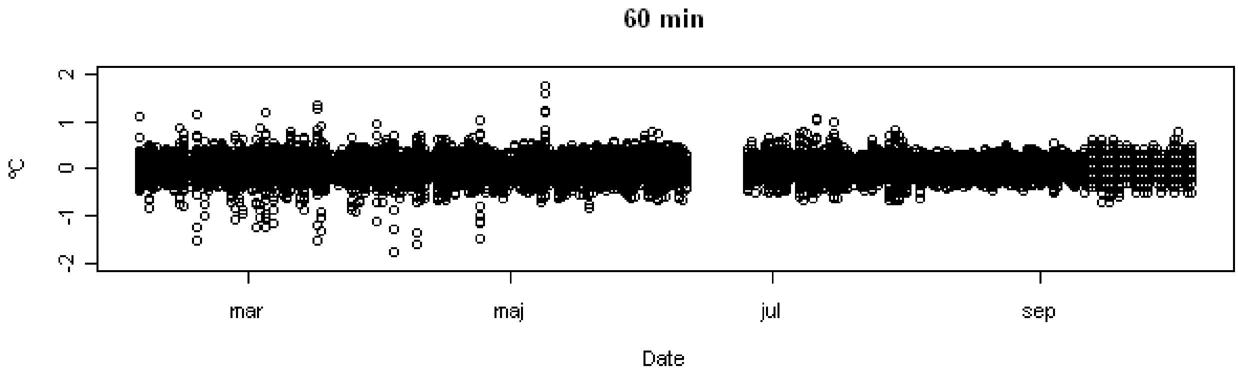
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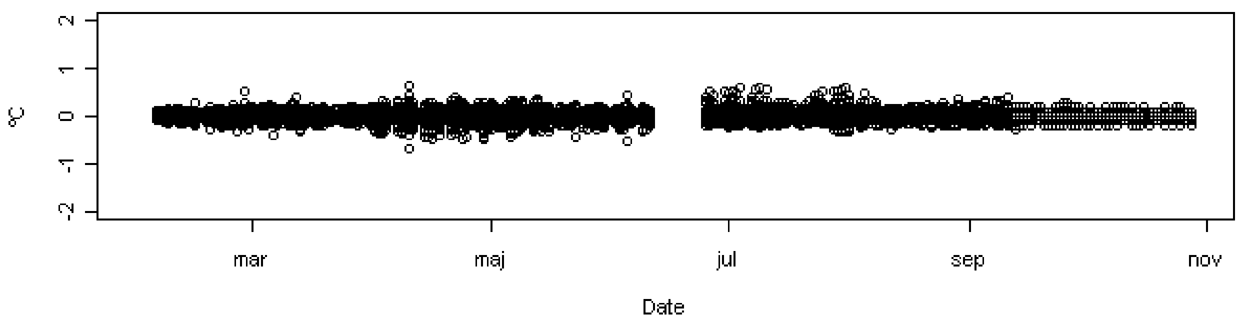
15 min



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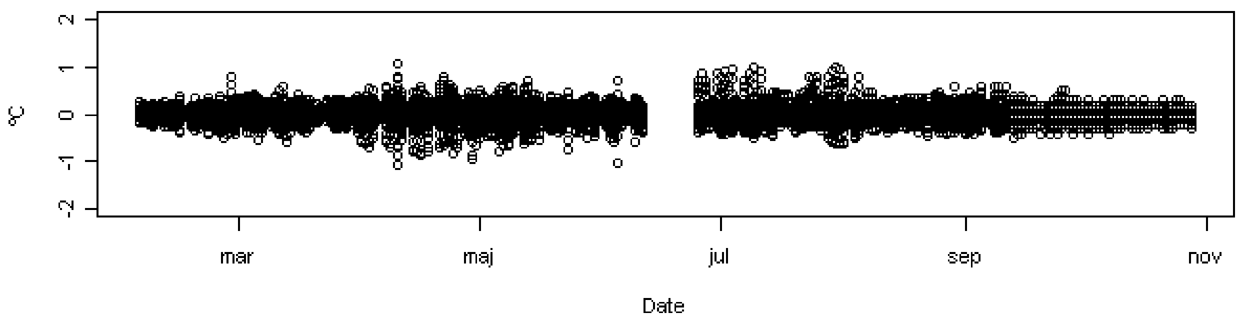

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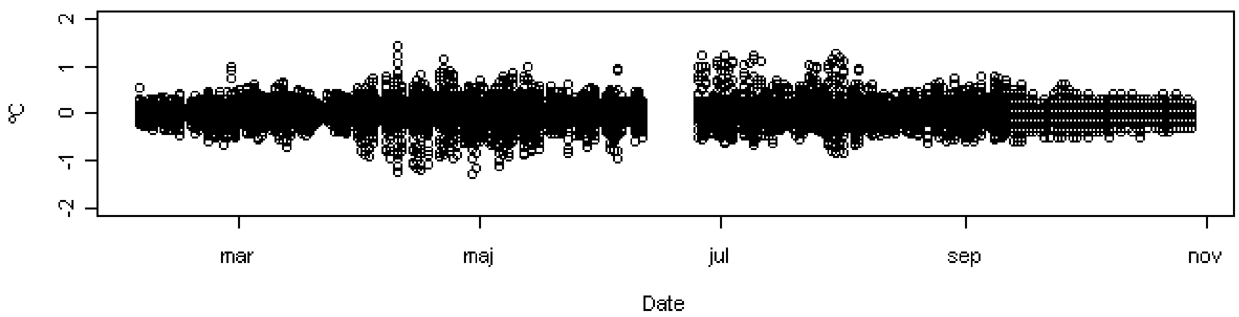

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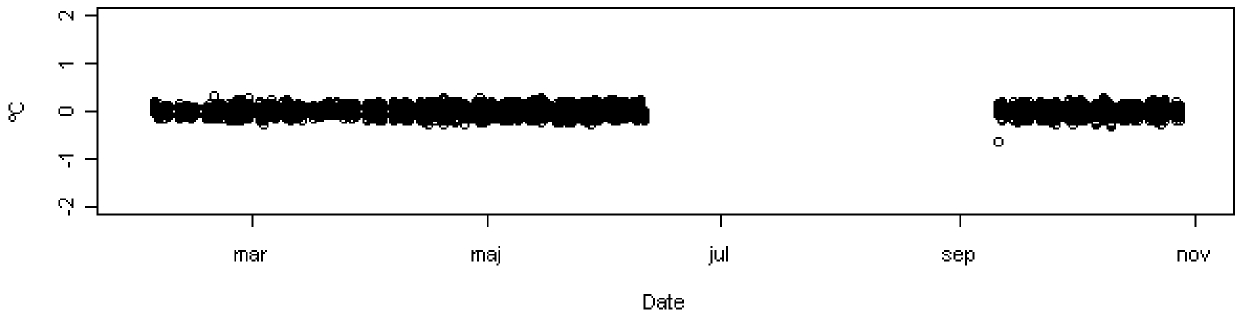

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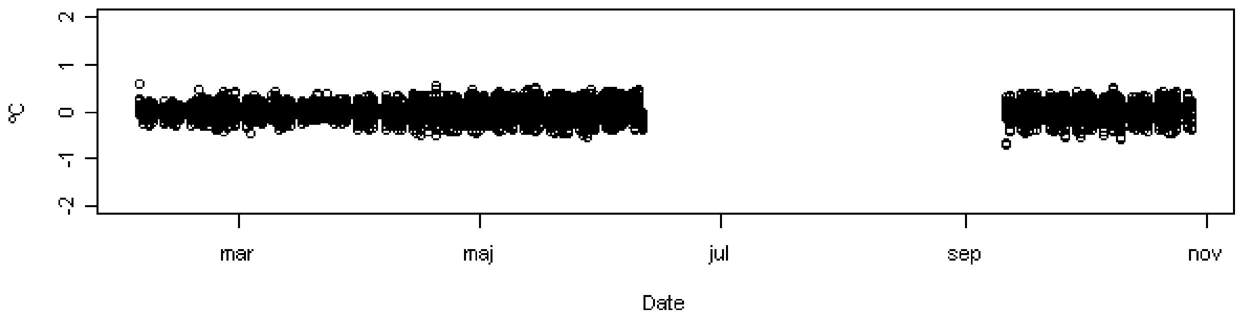

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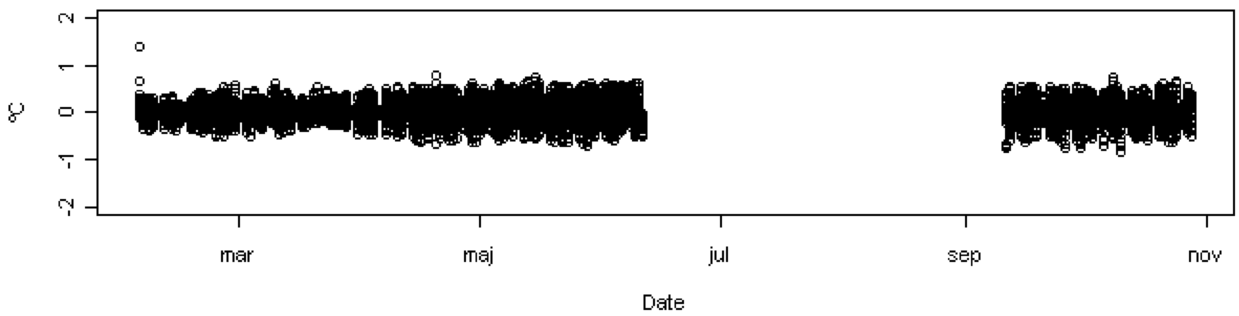

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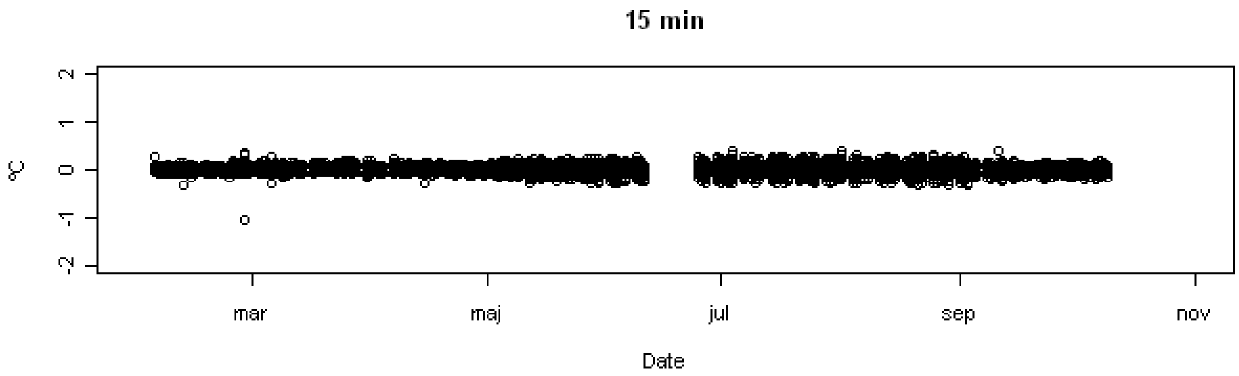
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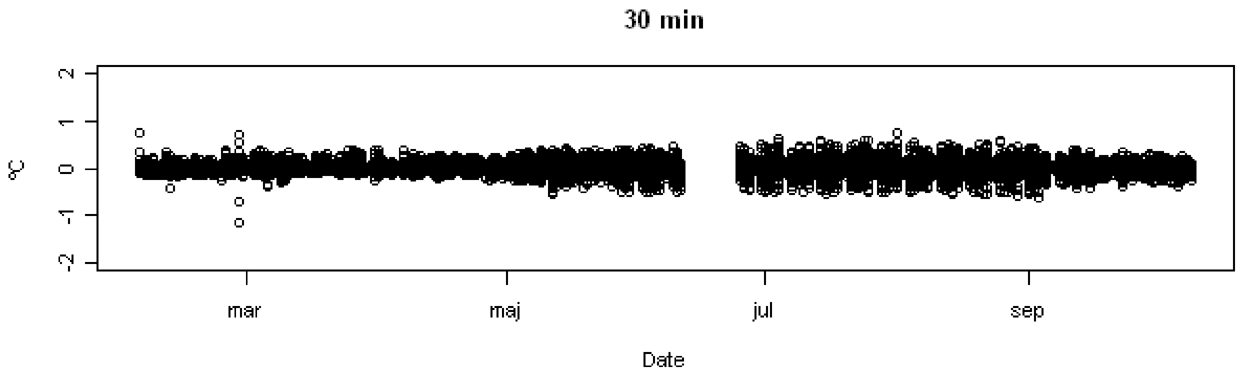
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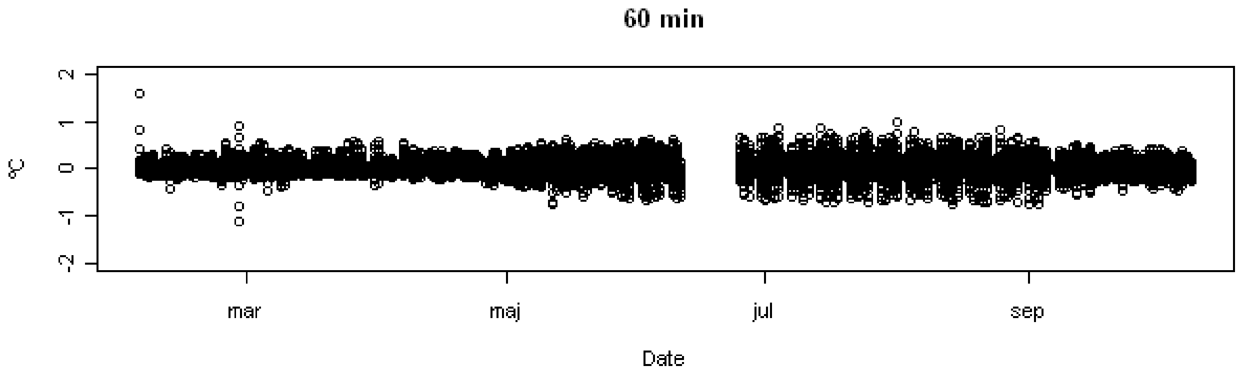
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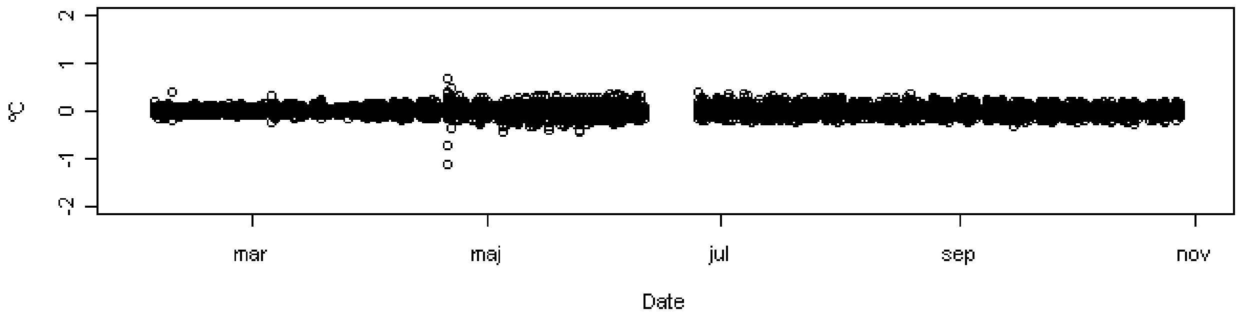

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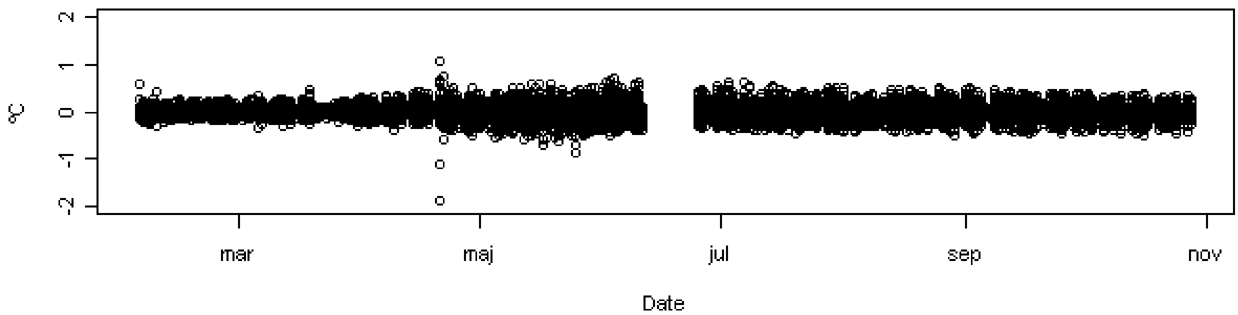

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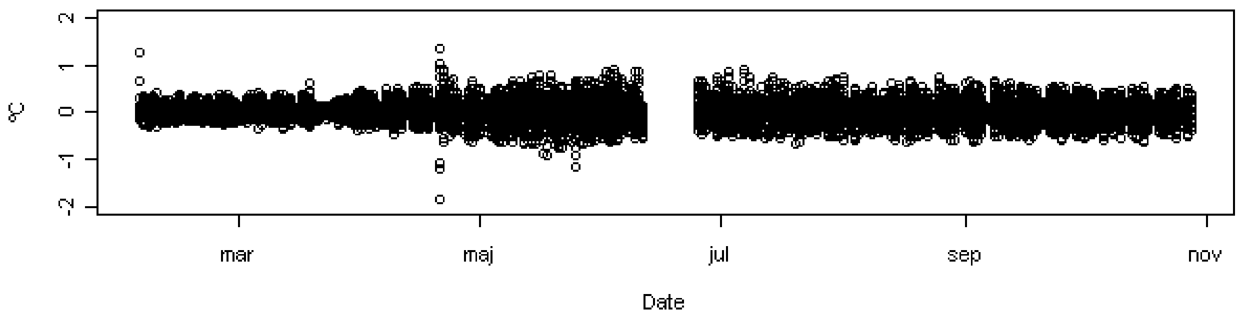

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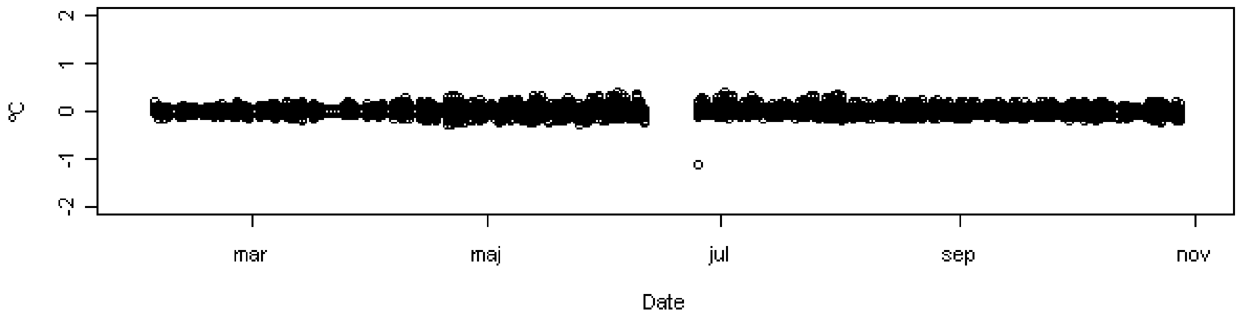

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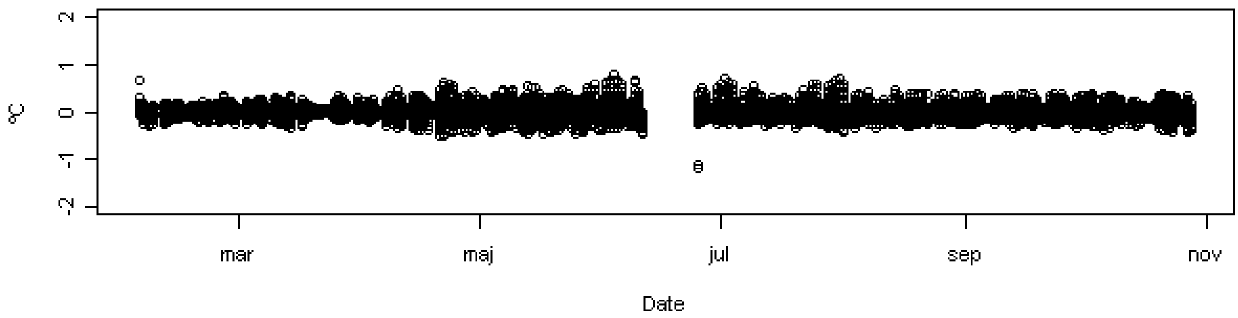

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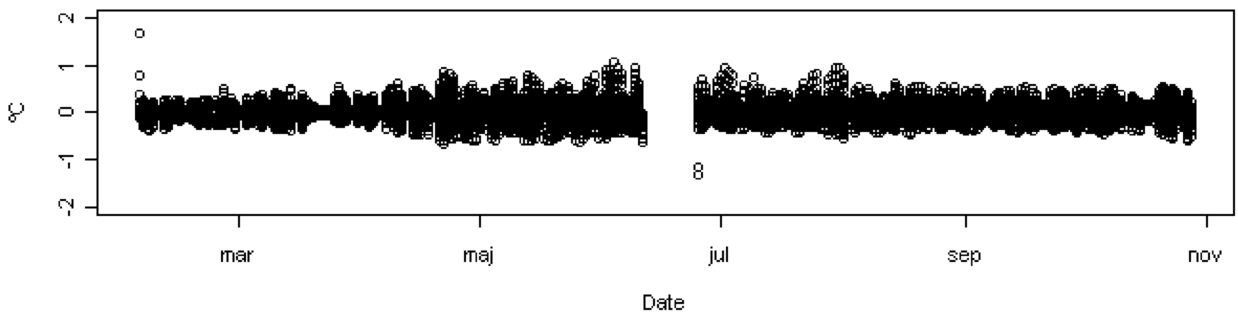

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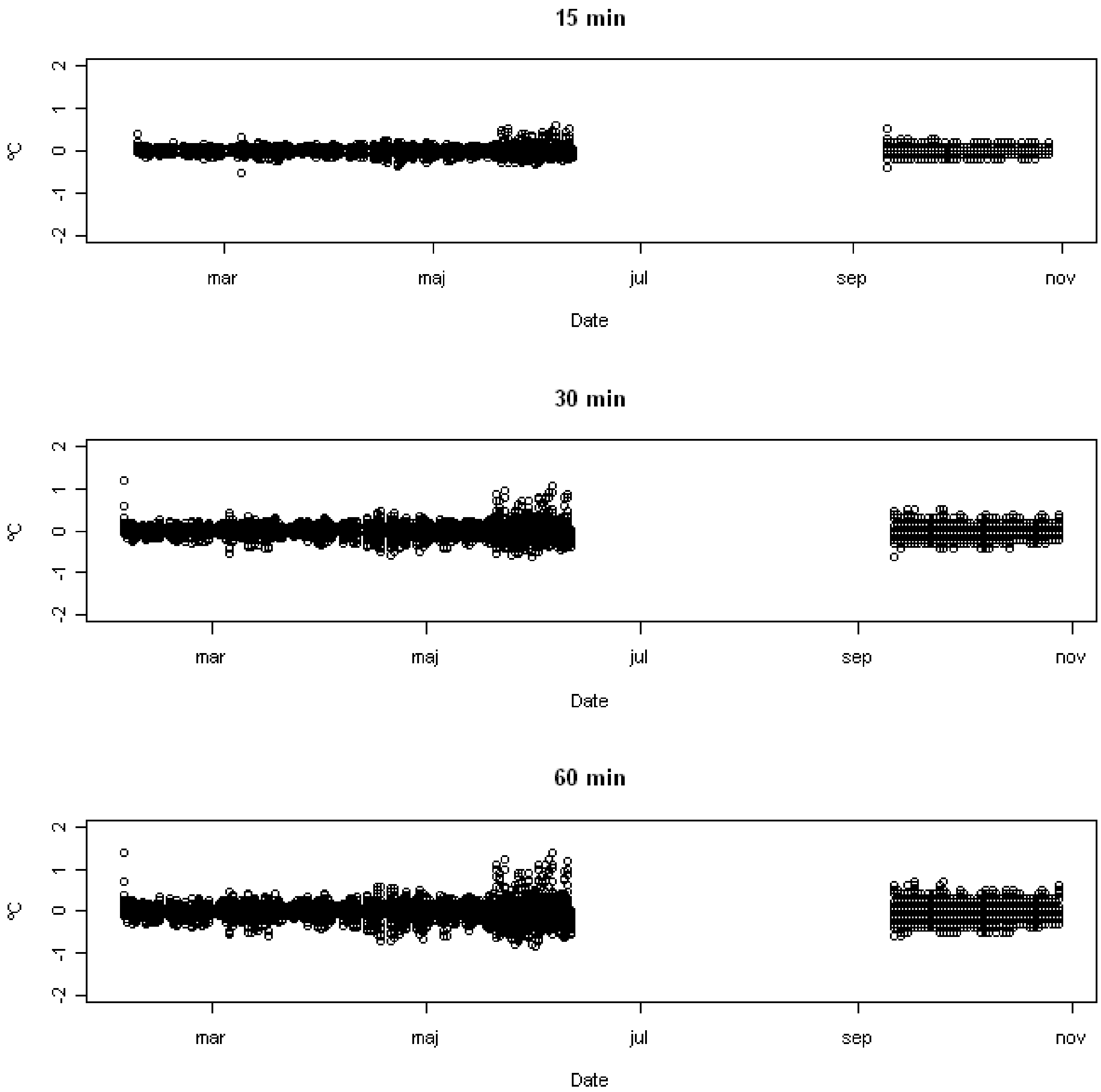
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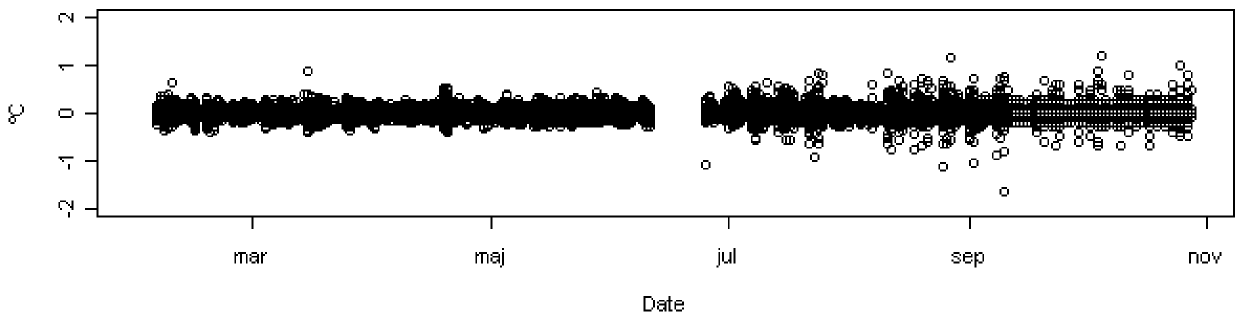

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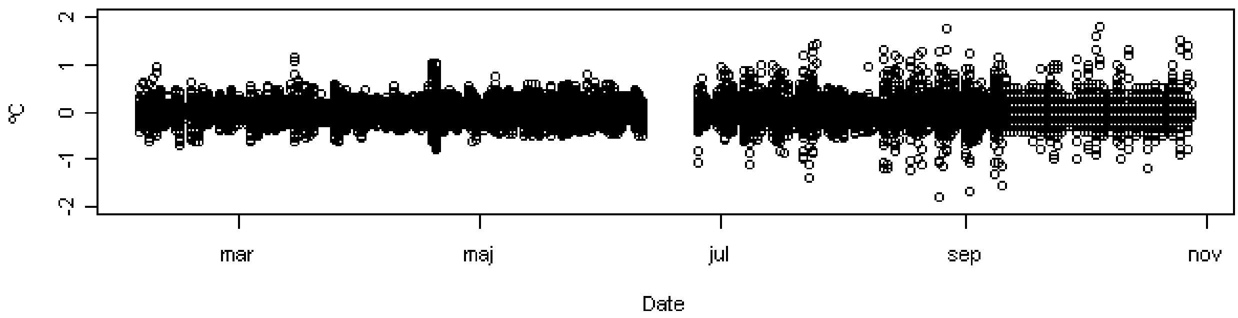

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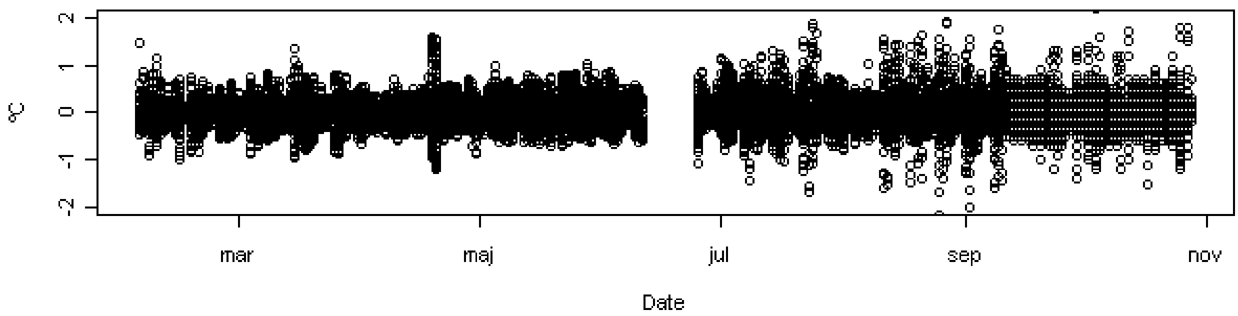

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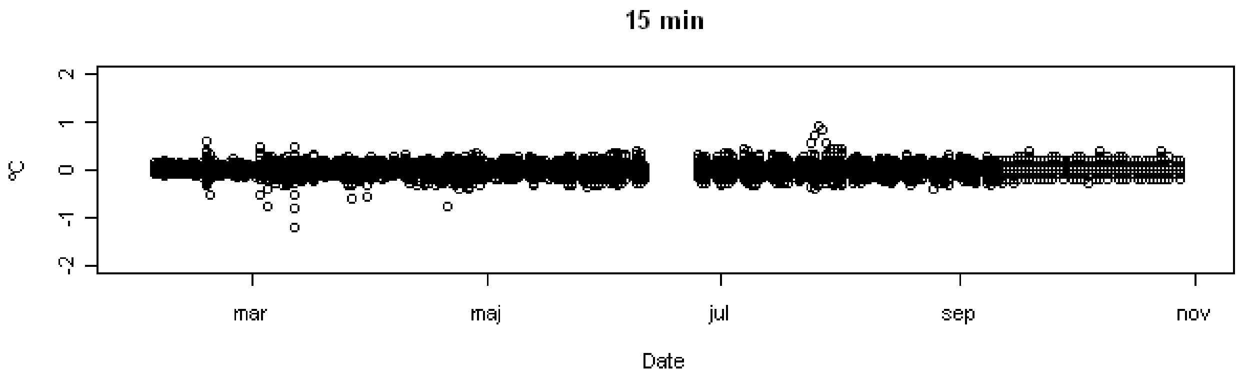
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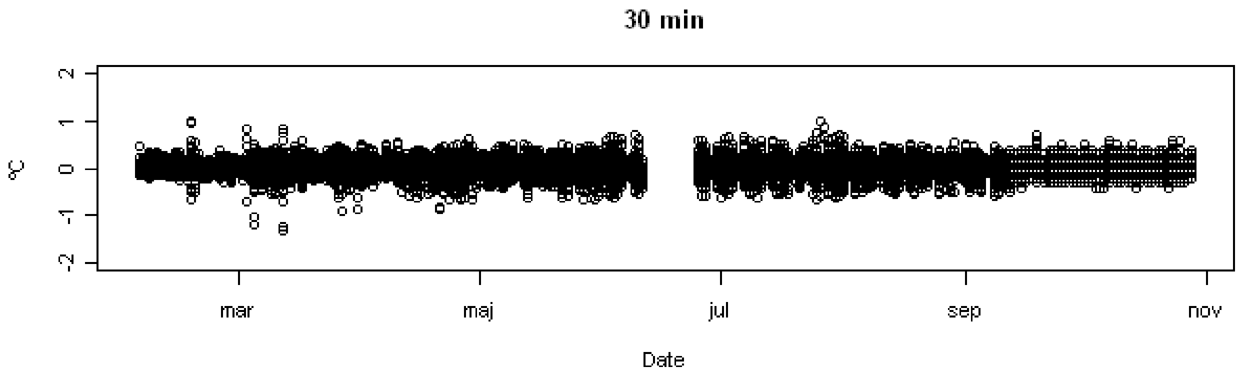
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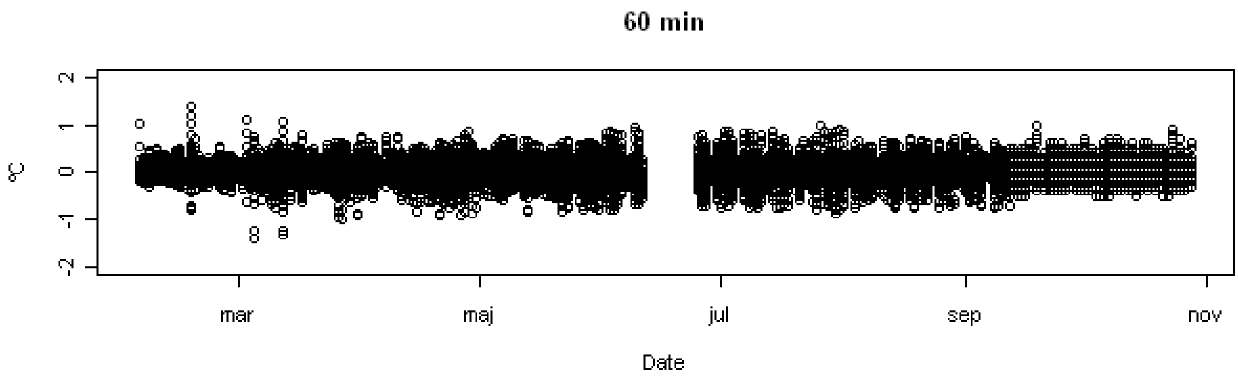
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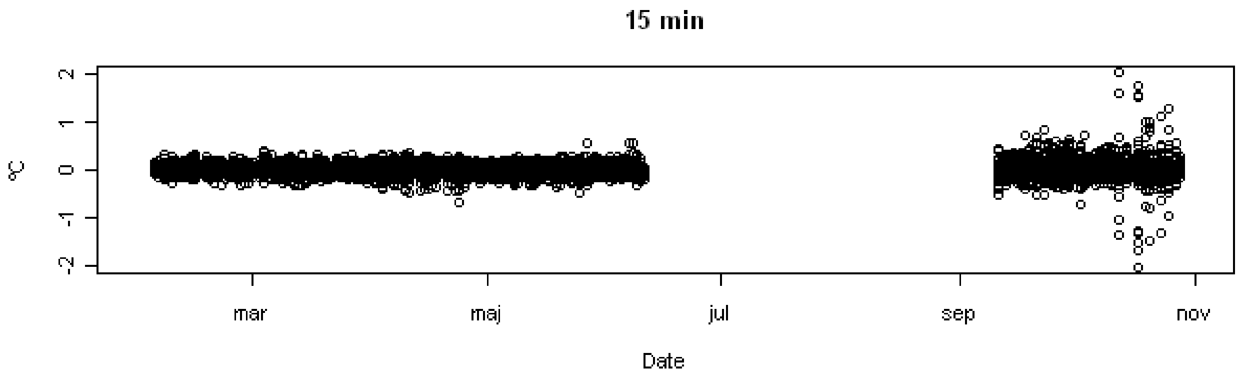
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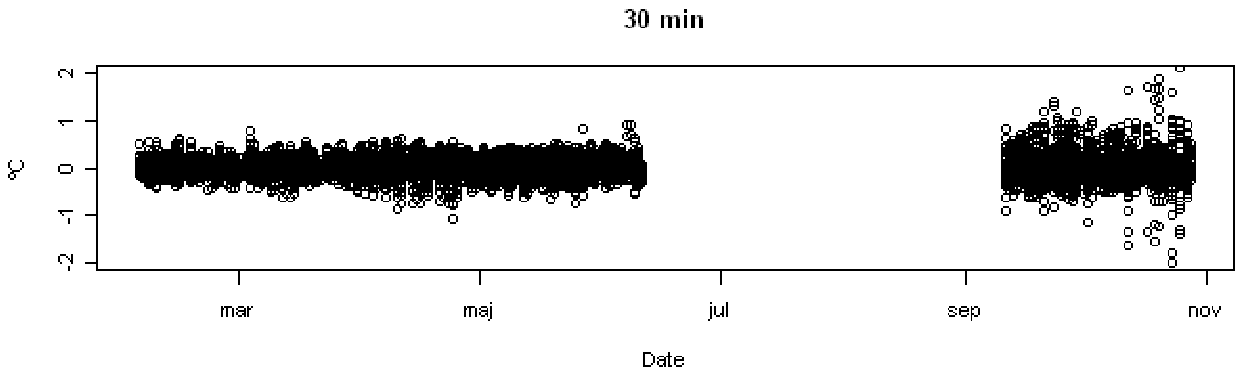
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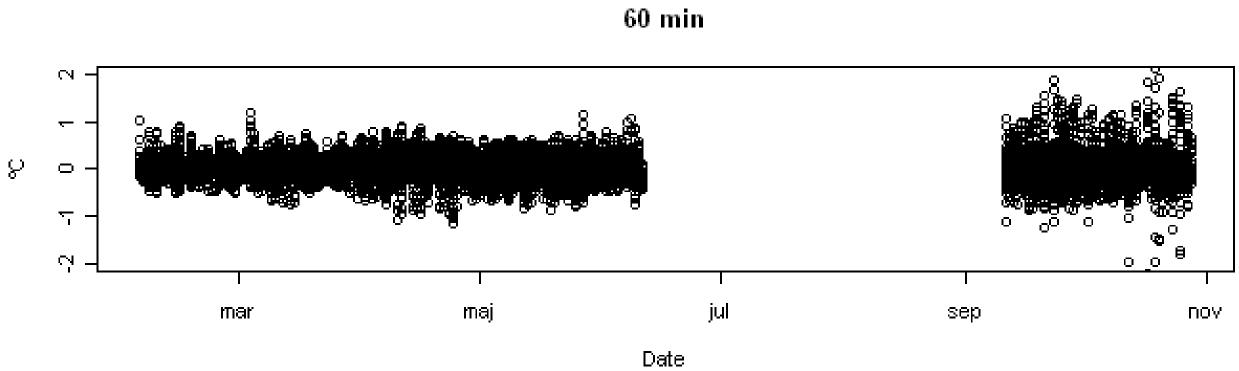
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Appendix 2.4a-b Summary of spot measurements on the 6 March 2008

Nearest logger	Floor	Zone	Height	Air temp. (ºC)	Op. temp. (ºC)	Air vel. (m/s)	Turbulence intensity (%)	DR	PMV	PPD
3028	0	Y1	0.1	23.3	22.8	0.16	50	17		
3028	0	Y1	0.6	23.3	22.9	0.15	47		0.1	5
3028	0	Y1	1.1	23.4	22.8	0.16	75	20		
3032	1	A1	0.1	23.5	22.9	0.11	73	11		
3032	1	A1	0.6	23.4	23	0.12	50		0.2	5
3032	1	A1	1.1	23.5	23	0.1	70	9		
3029	1	I3	0.1	22.7	22.6	0.1	50	9		
3029	1	I3	0.6	23	22.8	0.1	40		0.1	5
3029	1	I3	1.1	23.1	22.6	0.11	36	9		
3041	1	I4	0.1	23.4	22.6	0.13	38	11		
3033	1	I4	0.1	24.1	23.6	0.12	42	9		
3041	1	I4	0.6	23.1	22.4	0.09	67		0.1	5
3033	1	I4	0.6	24.1	23.4	0.11	82		0.4	8
3041	1	I4	1.1	23.8	22.8	0.07	71	5		
3033	1	I4	1.1	24.4	23.7	0.11	45	8		
3040	2	A1	0.1	22.8	22	0.12	83	15		
3040	2	A1	0.6	22.7	21.5	0.11	45		0.0	5
3040	2	A1	1.1	22.8	21.8	0.11	36	9		
3036	2	A3	0.1	23.1	22.7	0.11	100	14		
3036	2	A3	0.6	22.9	22.5	0.12	58		0.0	5
3036	2	A3	1.1	23	22.6	0.1	80	10		
3037	2	I3	0.1	22.9	22.6	0.16	50	17		
3037	2	I3	0.6	23.1	22.6	0.12	50		0.1	5
3037	2	I3	1.1	23.2	22.6	0.14	64	16		
3031	2	Y1	0.1	22.8	22.2	0.1	80	11		
3031	2	Y1	0.6	22.7	22	0.13	46		-0.1	5
3031	2	Y1	1.1	22.5	22	0.11	109	15		
3046	2	Y4	0.1	22.8	22.3	0.13	77	16		
3046	2	Y4	0.6	22.9	22.4	0.12	42		0.0	5
3046	2	Y4	1.1	23.1	22.4	0.08	50	6		
3039	4	A1	0.1	22.7	22.2	0.1	30	7		
3039	4	A1	0.6	22.6	22.3	0.09	111		0.0	5
3039	4	A1	1.1	22.7	22.2	0.16	75	22		
3038	4	I3	0.1	23.2	22.7	0.12	50	11		
3038	4	I3	0.6	23.2	22.6	0.11	55		0.1	5
3038	4	I3	1.1	23.3	22.7	0.12	75	13		
3042	4	Y4	0.1	23.1	22.5	0.07	14	3		
3042	4	Y4	0.6	23	22.4	0.08	88		0.1	5
3042	4	Y4	1.1	23.2	22.6	0.09	67	8		

Nearest logger	Floor	Zone	Height	Air temp. (ºC)	Op. temp. (ºC)	Air vel. (m/s)	Turbulence intensity (%)	DR	PMV	PPD
	0	A1	0.1	23.5		0.09	56	7		
	0	A1	0.6	23.7	23.4	0.09	44		-0.1	13
	0	A1	1.1	23.7		0.11	27	8		
3028	0	Y1	0.1	25.2		0.12	50	9		
3028	0	Y1	0.6	25.1	24.4	0.14	71		0.0	5
3028	0	Y1	1.1	25.2		0.1	70	8		
3032	1	A1	0.1	22.4		0.2	45	23		
3032	1	A1	0.6	22.4	22	0.21	48		-0.7	15
3032	1	A1	1.1	22.5		0.18	72	26		
	1	A3	0.1	23		0.12	58	12		
	1	A3	0.6	23.2	22.8	0.08	38		-0.3	7
	1	A3	1.1	23.3		0.07	43	4		
3029	1	I3	0.1	22.9		0.18	50	20		
3029	1	I3	0.6	23.3	23	0.16	69		-0.7	15
3029	1	I3	1.1	23.3		0.13	46	12		
3041	1	I4	0.1	22.2		0.1	50	9		
3033	1	I4	0.1	23.7		0.08	50	5		
3041	1	I4	0.6	22.3	22	0.15	40		-0.7	15
3033	1	I4	0.6	23.8	23.3	0.1	40		-0.2	6
3041	1	I4	1.1	22.3		0.13	54	14		
3033	1	I4	1.1	23.9		0.07	71	4		
3040	2	A1	0.1	23.4		0.12	50	11		
3040	2	A1	0.6	23.4	23	0.08	50		-0.3	6
3040	2	A1	1.1	23.4		0.09	56	7		
3037	2	I3	0.1	22.7		0.14	36	13		
3037	2	I3	0.6	22.7	22.4	0.14	43		-0.5	11
3037	2	I3	1.1	22.7		0.08	88	7		
3031	2	Y1	0.1	23.6		0.15	47	14		
3031	2	Y1	0.6	23.7	23.3	0.09	67		-0.2	6
3031	2	Y1	1.1	23.7		0.06	67	3		
3046	2	Y4	0.1	23.3		0.11	55	10		
3046	2	Y4	0.6	23.1	22.9	0.13	46		-0.4	8
3046	2	Y4	1.1	23.2		0.09	78	8		
3039	4	A1	0.1	22.7		0.1	50	9		
3039	4	A1	0.6	22.8	22.5	0.05	80		-0.4	8
3039	4	A1	1.1	22.8		0.05	80	0		
3038	4	I3	0.1	23.1		0.06	67	3		
3038	4	I3	0.6	23.2	22.6	0.08	63		-0.4	8
3038	4	I3	1.1	23.2		0.08	63	6		
3042	4	I4	0.1	22.3		0.1	50	9		
3042	4	I4	0.6	22.5	22.1	0.09	78		-0.5	10
3042	4	I4	1.1	22.6		0.12	75	14		

Appendix 2.5 Comments from the occupants on the indoor environment

Her er skiftende koldt/varmt, dårlig luft, meget støjende (eftersom man sidder i åbent miljø). Man får røde og irriterede øjne hen over middag samt ofte hovedpine og bliver utilpas.

I løbet af eftermiddagen er det klart ubehageligt at sidde to personer i det lille kontor, hvor jeg sidder, og der er ca. 25 grader om eftermiddagen, selv om der aldrig er nogen sol, der står på. Luften er også ""dårlig"", manglende ilttilførsel til rummet, og man er "godt brugt", når man går hjem. Dog ingen hovedpine, bare træt.

mht. varmen i kontoret - lige nu er her altså ret køligt og det trækker et eller andet sted fra. men ellers må jeg nok tilføje at her er for varmt det meste af tiden. Det der sådan set, er det værste for mig er, her er alt for meget lys.

De problemer jeg oplever er, alt for tit alt for varmt, det gør at jeg bliver temmelig dvask. I skrivende stund "morgen" er her én behagelig temperatur, men mod middagstid bliver den noget højere.

Ingen mulighed for at udluftning eller gennemtræk, intet normalt dagslys - kun fra ovenlys atriumgård, megen persongennemgang i kontoret, støjgener fra kolleger- adfærd omkring tale, tlf. mv bør oplyses bedre.

Dårligt. Støjende / snavset / støvet / mørkt / ubehageligt / generelt ganske utilfredsstillende

Problemet i vores lokale er ikke temperaturen, men at det trækker.

Det trækker ad h.t. især når der er trafik ud og ind af opgangen, så kommer det et sus af kold luft.

Luften er ok om morgen, men opad dagen bliver den tung, tør og varm.

Jeg har altid tørre hænder, læber, mund og hals. Det er altid enten rigtig varmt eller rigtig koldt. Det føles som om der aldrig er luftudskiftning i rummet og det får jeg let hovedpine af. Desuden lugter der altid af et eller andet ubeskriveligt i lokalet. Jeg tror lugten kommer fra kantinen, når de laver mad også når mine kolleger spiser deres medbragte mad ved bordet. Desuden sidder vi ekstremt tæt og når folk taler i telefon på samme tid, er det slet ikke til at være her for larm.

Her er generelt for varmt. Dog kan temperaturen svinge. Om sommeren er her for koldt. Det værste er støj, dårlig luft (mangel på ilt) og manglende sollys.

Jeg har netop nu været på arbejde i en halv time, og klokken er 9:20. Der er som regel rart at være tidligt på dagen. Efter frokost kommer generne (når de er der).

Jeg arbejder bedst, når her ikke er for varmt. Men når her er køligt (fordi vejret uden for er det), kan jeg tydeligt mærke, at det "kulder" ind fra mit vindue (jeg sidder med venstre side til vinduet), og det er vel en "forkert" måde, luften bevæger sig på.

Da de fleste ansatte sidder i et åbent kontorlandskab er støj og gentagne afbrydelser fra flere sider det der generer mig mest, når jeg har en opgave der kræver ekstra koncentration.

Lige nu er temperaturen okay, men f.eks. om sommeren når solen skinner så har vi mellem 25 og 27 grader om eftermiddagen, og det er meget ubehageligt.

Indeklimaet i kopirum er ekstremt dårlig. Hvis der printes /kopieres store mængder er lugten dårlig og luften tør, så døren til rummet står altid åben - med det resultat, at både dårlig lugt og støj kommer ud i rummet.

Der er typisk normal temperatur eller køligt om morgenen og det er også der jeg mærker meget træk/blæst fra ventilationen i loftet over mig. Efter frokost er her for varmt og indelukket, men der er stadigvæk træk fra ventilationen, på trods af den højere temperatur.
På vores lille kontor er problemet stillestående luft og iltmangel, dårlig og tungt indeklima, ingen luftudskiftning.

Min frustration er at jeg gerne ville have mere frisk luft, men øget cirkulation betyder mere træk, og jeg kan ikke tåle træk

For lidt luftcirkulation, for tør luft, rimeligt store temperatursvingninger så der er koldt om eftermiddagen, for lidt dagslys.

Der er meget store komfort forskelle på om man sidder tæt ved vinduer (meget dårlige forhold: for koldt når det er koldt i lokalet, for varmt når det er varmt i lokalet) og når man ikke gør.

Jeg har generelt ingen problememer med at sidde i storrum. Støj og varme generer mig sjældent. Jeg ved godt at jeg er en meget unormal kvinde.

Det er formiddag, og luften er stadig forholdsvis frisk.

Oven lyset er generelt for skarpt og der er ikke mulighed for at dæmpe lyset. Temperaturen er generelt for høj og vi åbner dagligt vinduet for at forbedre luften og temperaturen i kontoret.

Til tider svært at koncentrere sig pga. støj fra kolleger, når der tales i telefon. Vi sidder 8 kolleger (2 x 4) med mange telefoner daglig.

Det værste er, at indeklimaet ikke er konstant. Nogle dage er der alt for koldt, nogle dage alt for varmt, nogle dage al for tung luft osv.

Netop nu er klimaet ok, men over middag bliver der normalt meget varmt eller meget koldt og dårlig luft. Desuden er her generelt ikke lyst nok, hvilket gør, at man bliver lidt sløv...

Generelt synes jeg klimaet er ok - kunne være lækkert, hvis man kunne slippe for nyseri og tør næse

Det trækker jævnligt. Der bør ikke være borde i midten af lokalerne, der bør være mødelokaler e.l. Der er for mørkt og alt for meget støj. Generelt mangler der "udsmykning" /omgivelser der skaber ro, balance og energi!

Mit store problem er lys. Og så at temperaturen ændrer sig flere gange i løbet af en uge....

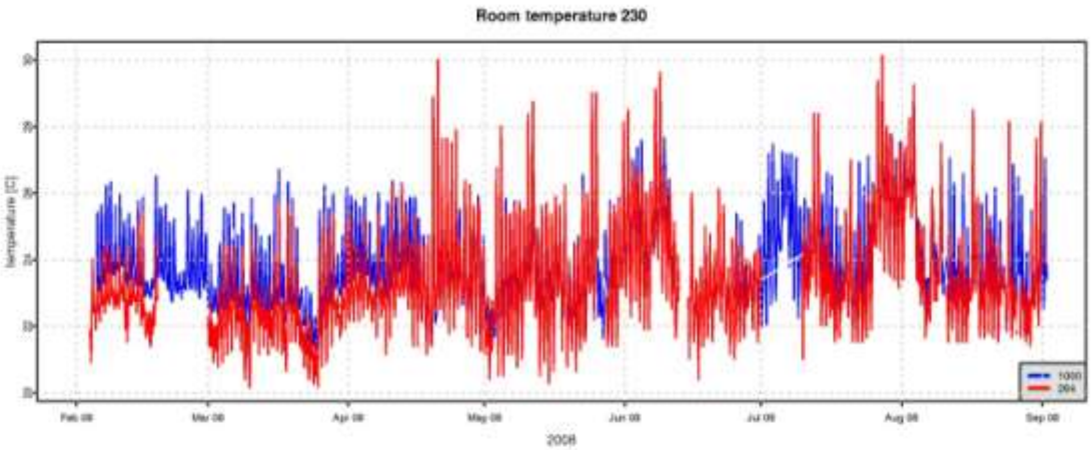
Jeg er ikke sikker på at temperaturen er for lav, men jeg fryser tit (skutter mig lidt). Jeg synes det er som om jeg sidder i træk. Mht hvorvidt her er snavset eller rent synes jeg umiddelbart her er pænt rent, men her roder helt vildt, og det synes jeg skaber et uroligt arbejdsklima.

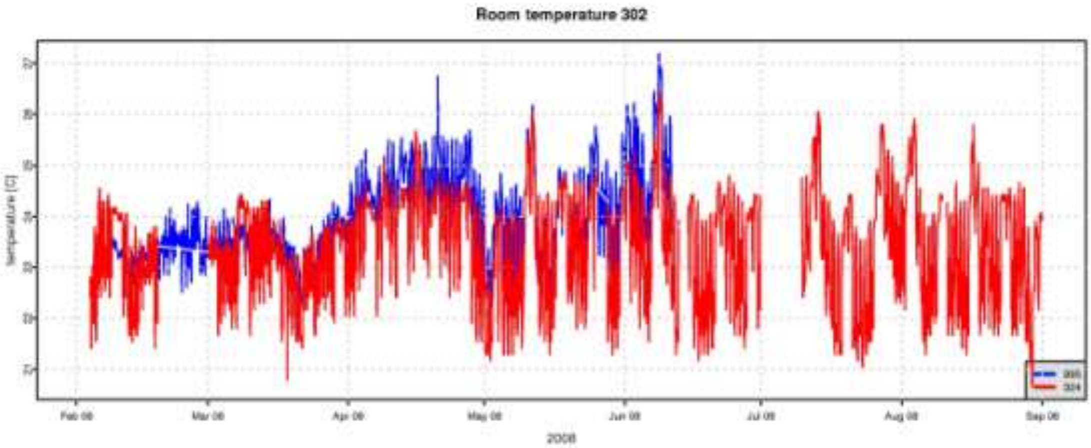
Om formiddagen er luften bedre tempereret end om eftermiddagen hvor det er nærmest uud-holdeligt med tungt hoved og hævede fødder.

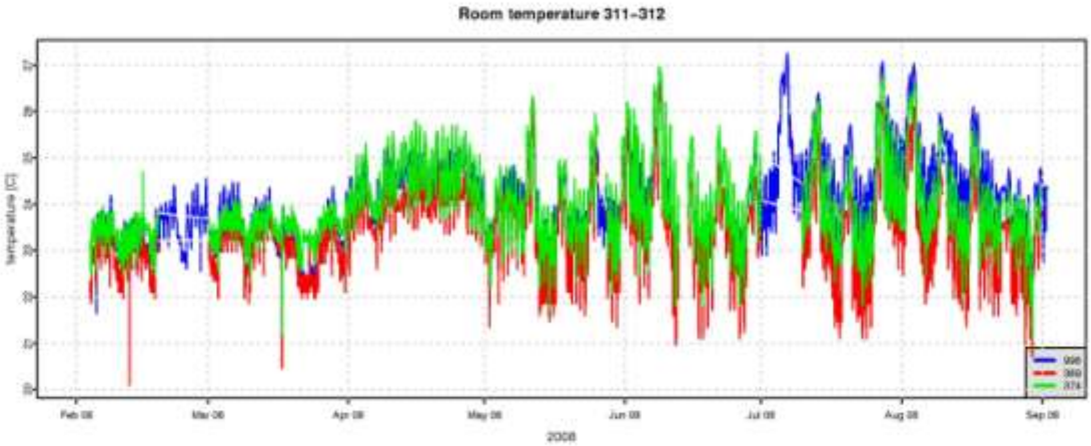
Det trækker med ret kold luft.

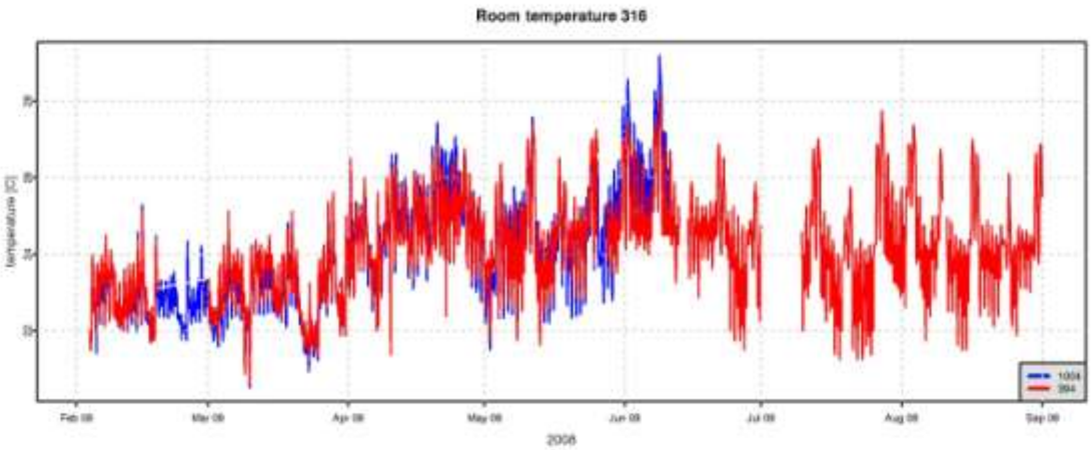
Som udgangspunkt meget tilfreds, men der kan til tider godt trække kolde vinde fra loftet

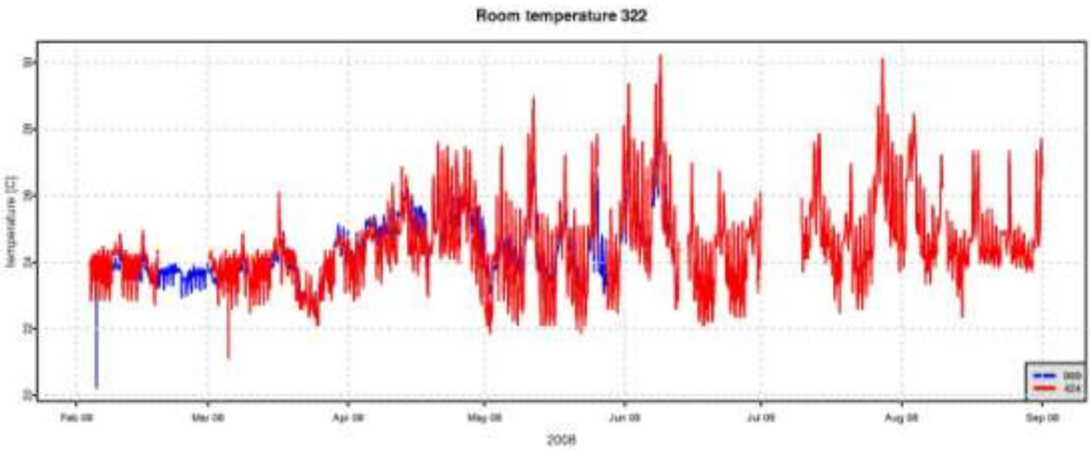
Appendix 3 Comparison between BMS and special purpose data

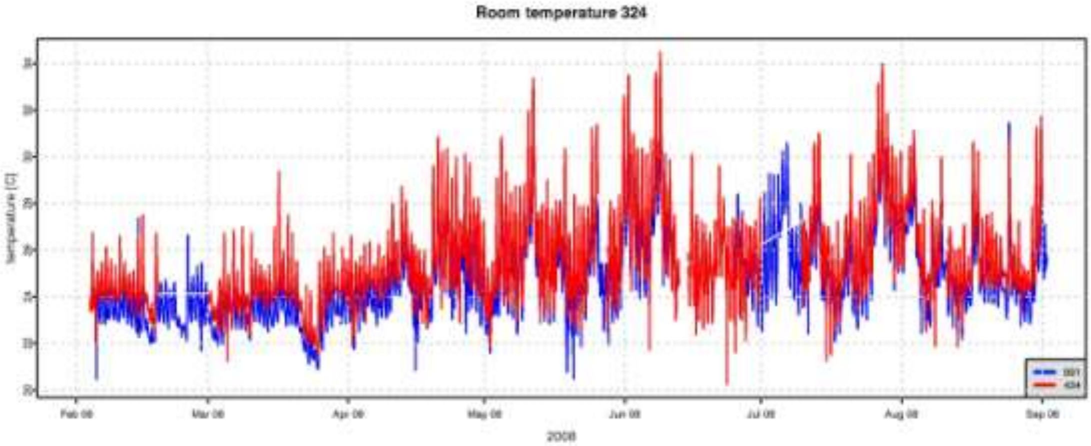


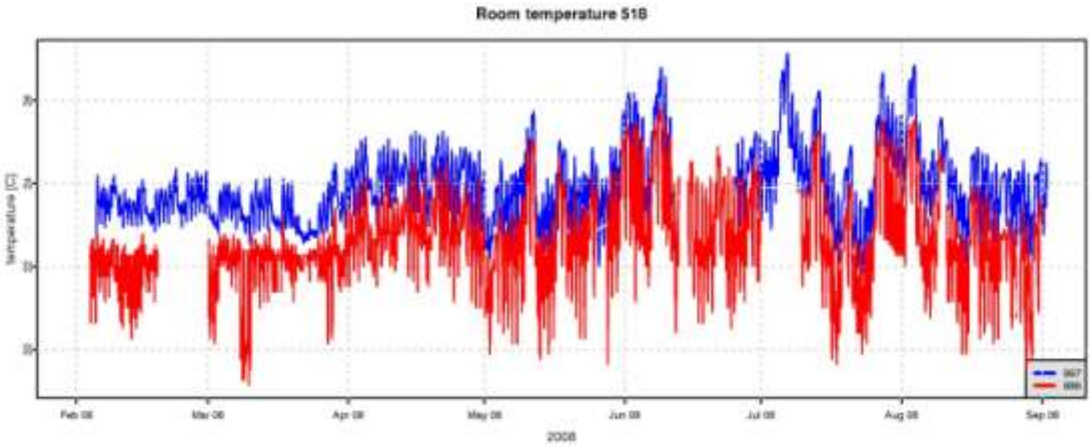


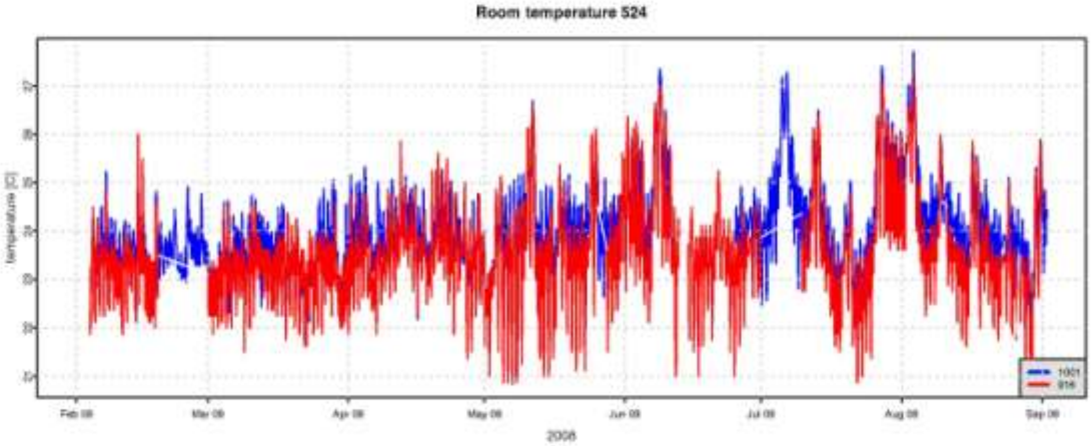


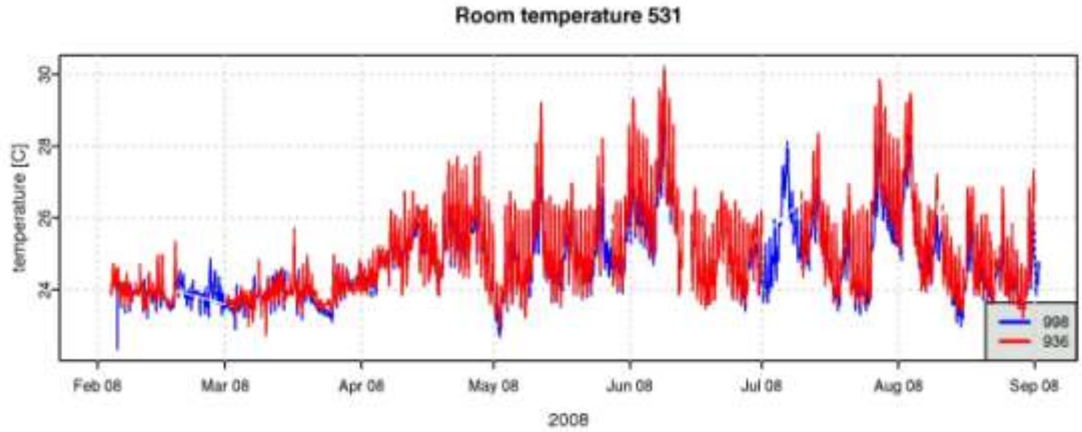


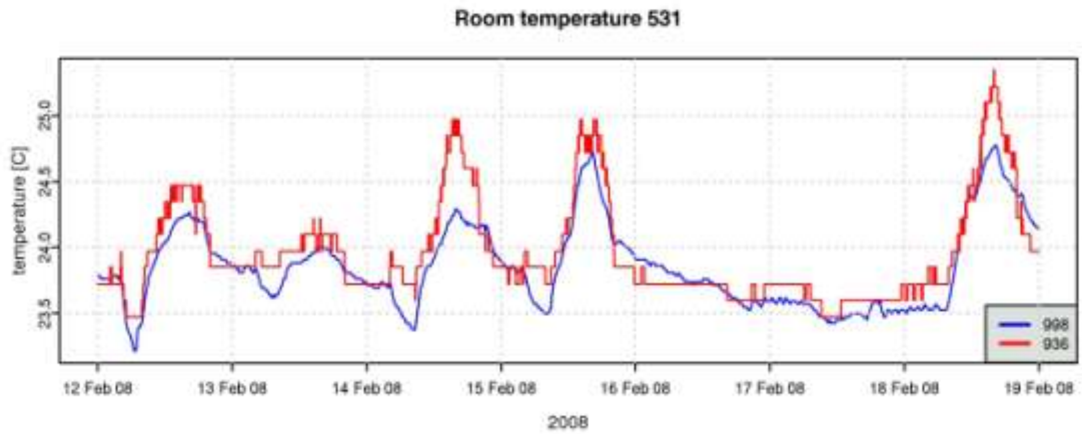

Room temperature 322
2008


Room temperature 324
2008


Room temperature 518
2008


Room temperature 524
2008


Room temperature 531
temperature [C]
24
26
28
30
Feb 08
Mar 08
Apr 08
May 08
Jun 08
Jul 08
Aug 08
Sep 08
2008
998
936


Room temperature 531
temperature [C]
23.5
24.0
24.5
25.0
12 Feb 08
13 Feb 08
14 Feb 08
15 Feb 08
16 Feb 08
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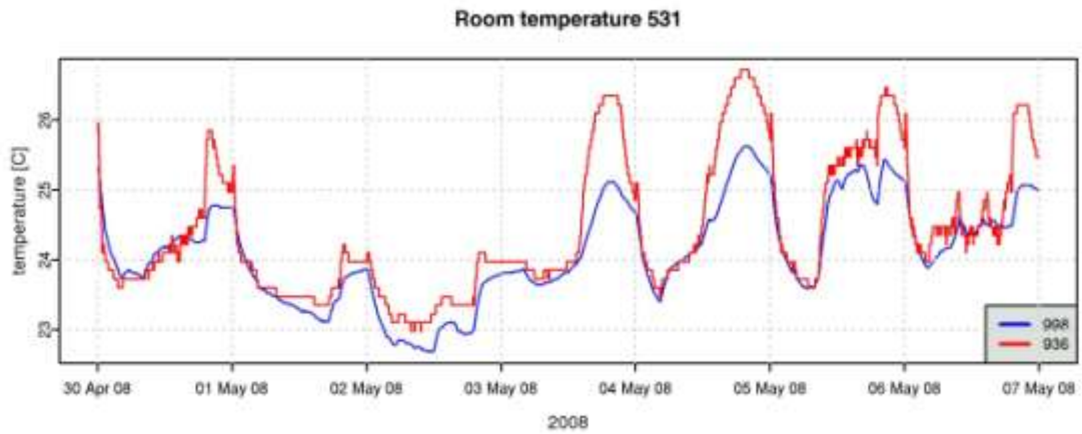
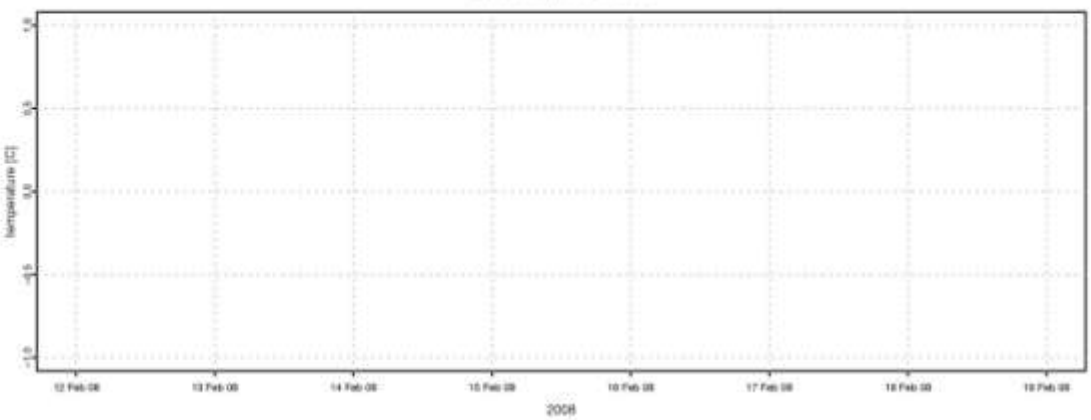
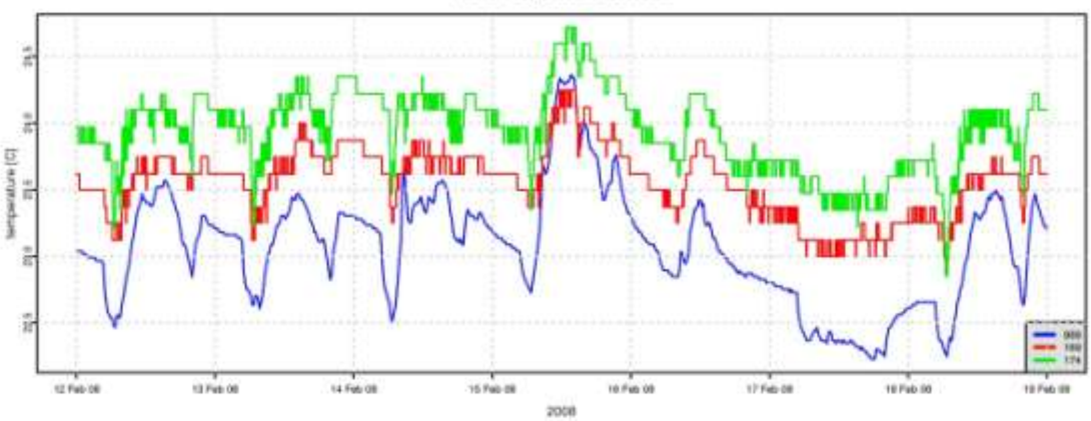
19 Feb 08
2008
998
936


Room temperature 531
temperature [C]
23
24
25
26
30 Apr 08
01 May 08
02 May 08
03 May 08
04 May 08
05 May 08
06 May 08
07 May 08
2008
998
936

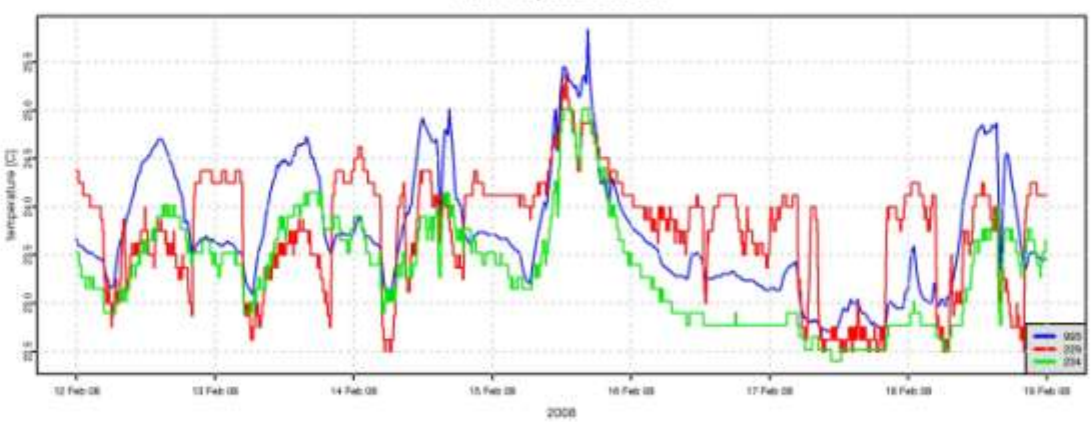
Room temperature 113



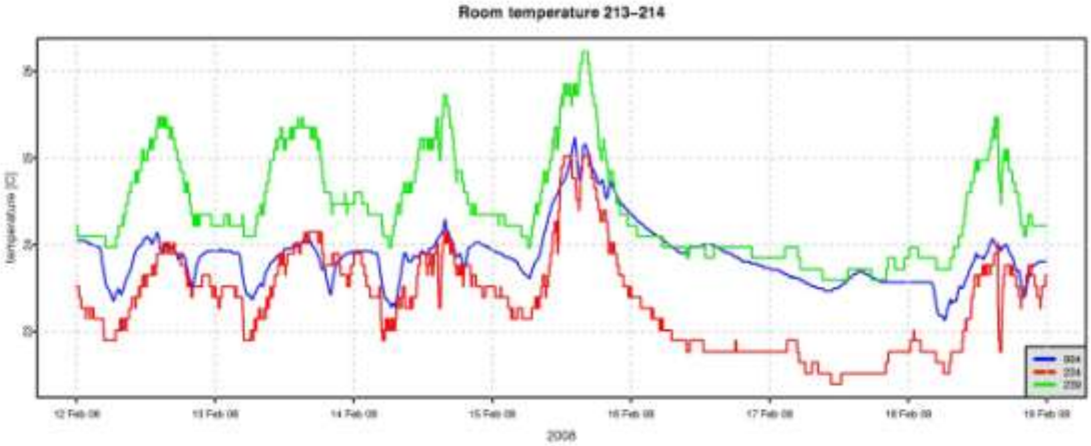
Room temperature 201–202



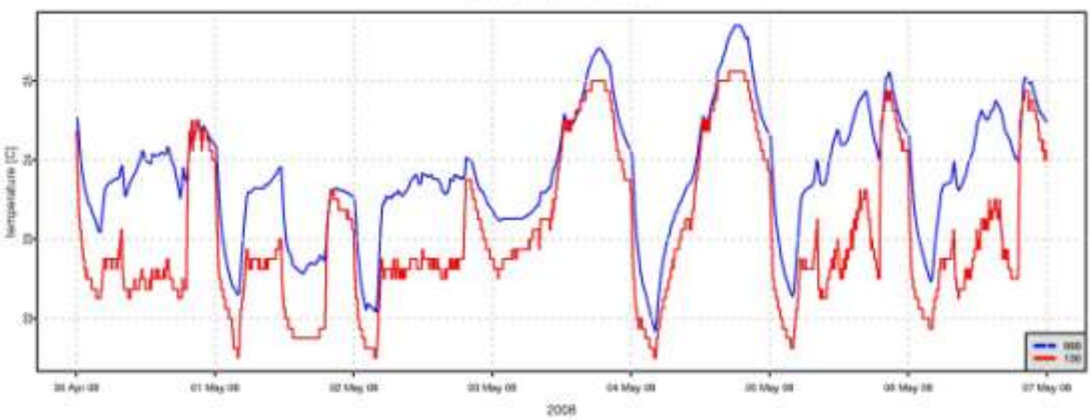
Room temperature 212–213



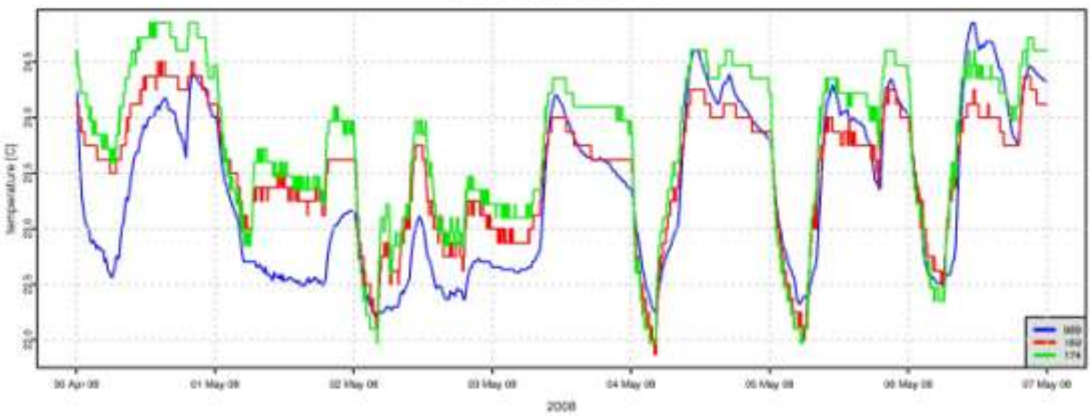
Room temperature 213–214



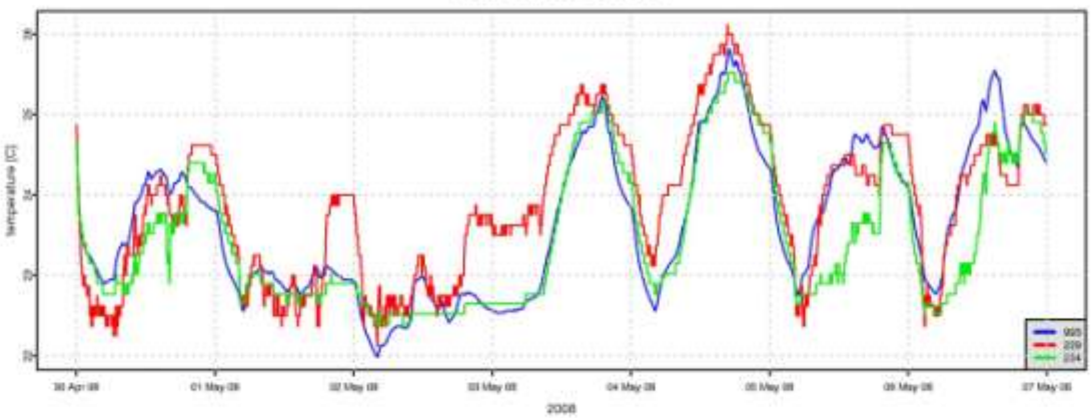
Room temperature 113



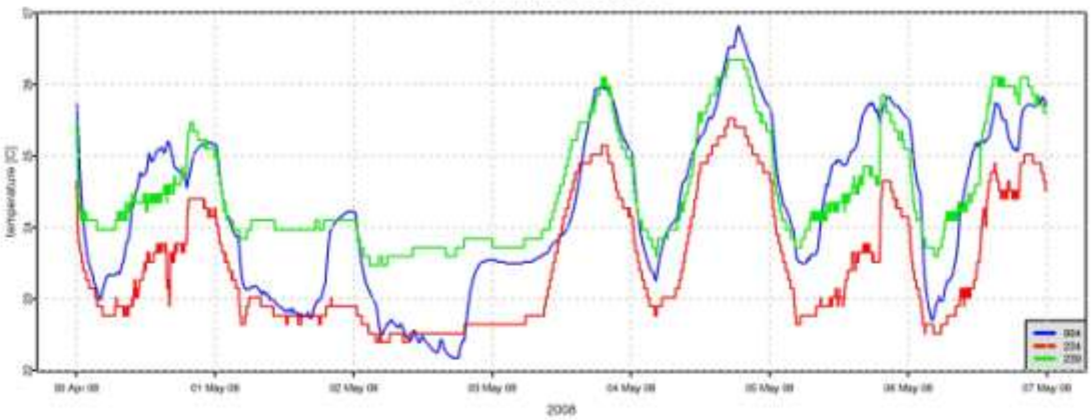
Room temperature 201-202

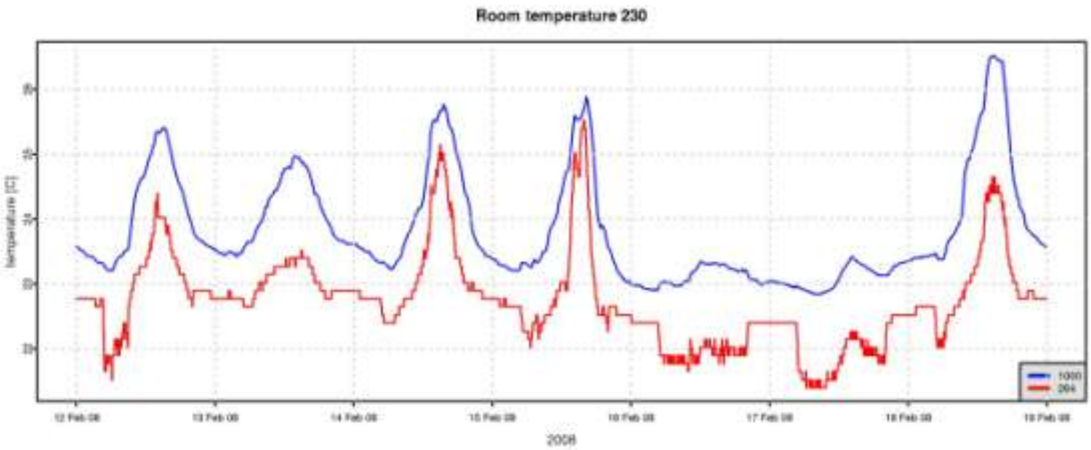


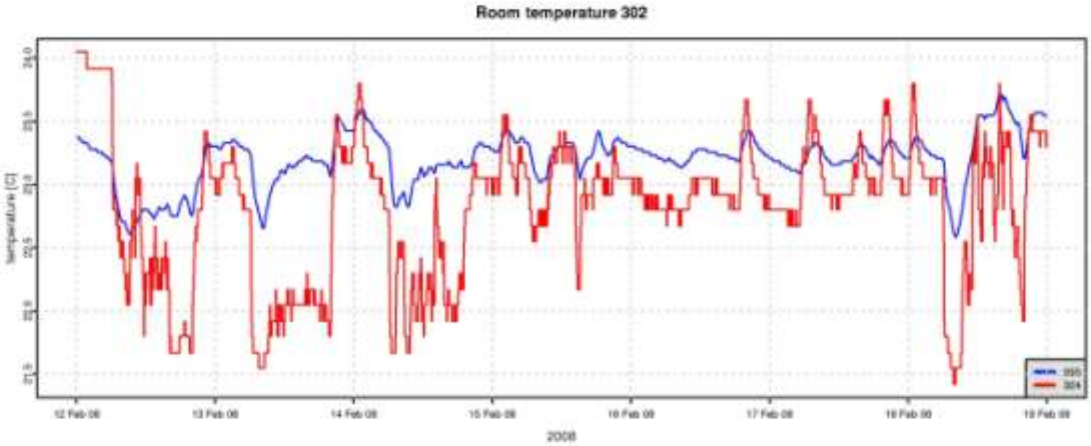
Room temperature 212-213

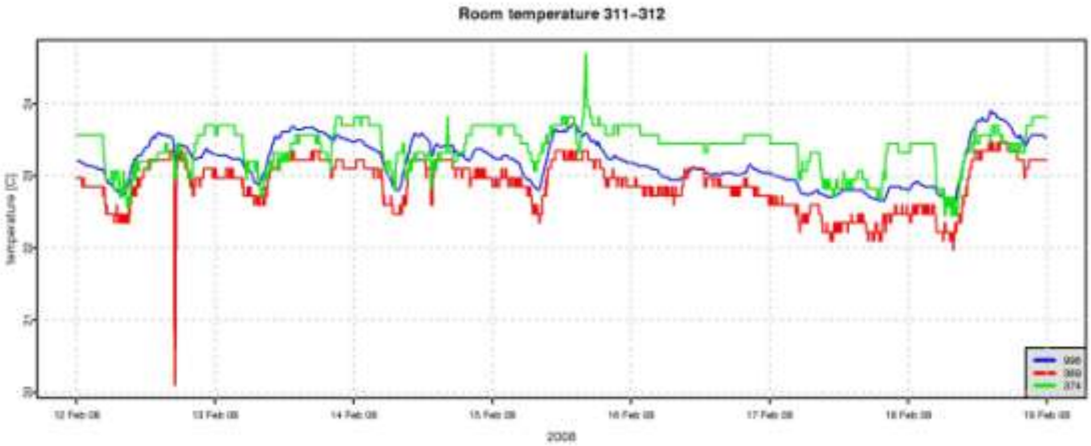


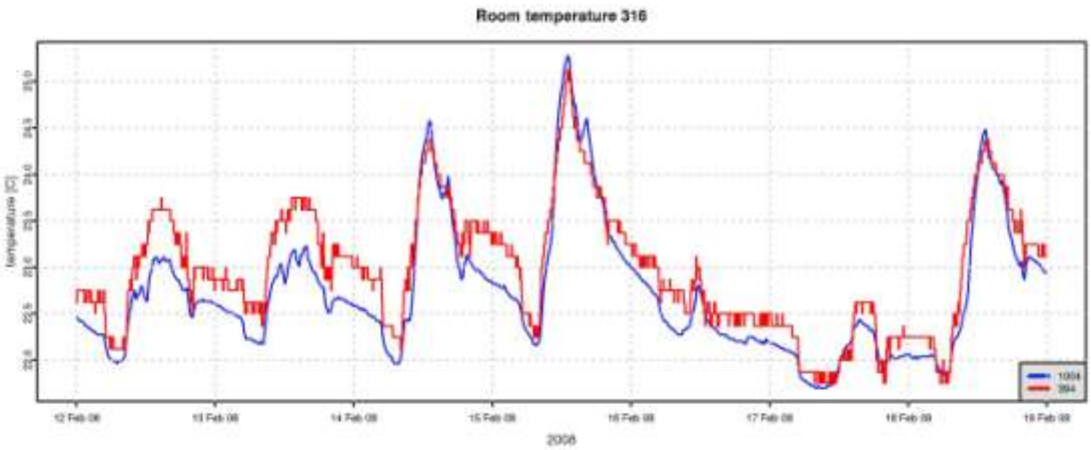
Room temperature 213-214



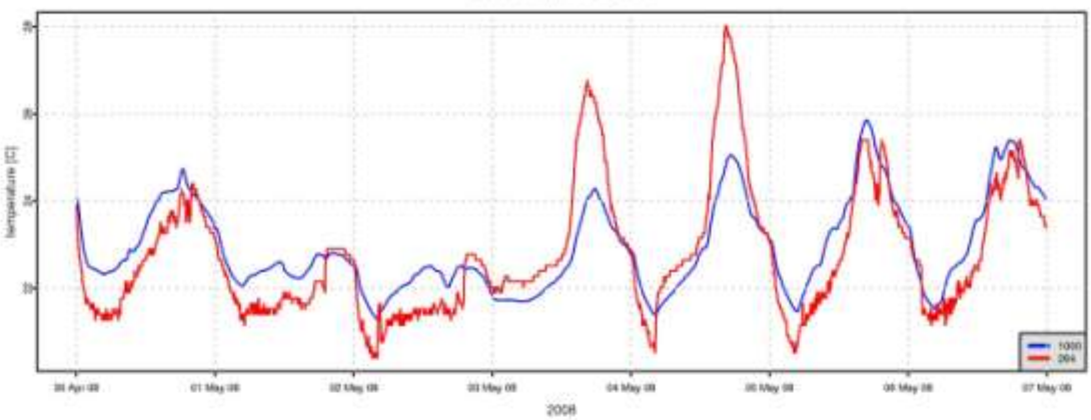

Room temperature 230
Temperature [C]
2008


Room temperature 302
Temperature [C]
2008

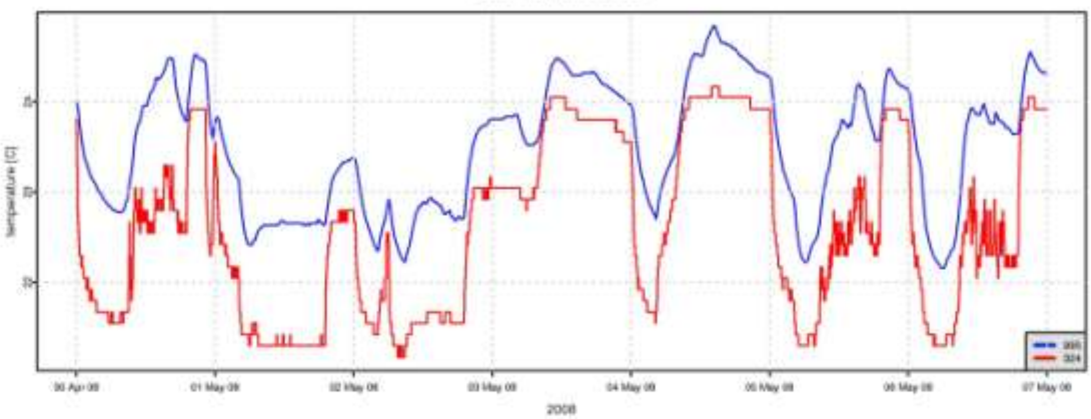

Room temperature 311-312
Temperature [C]
2008


Room temperature 316
Temperature [C]
2008

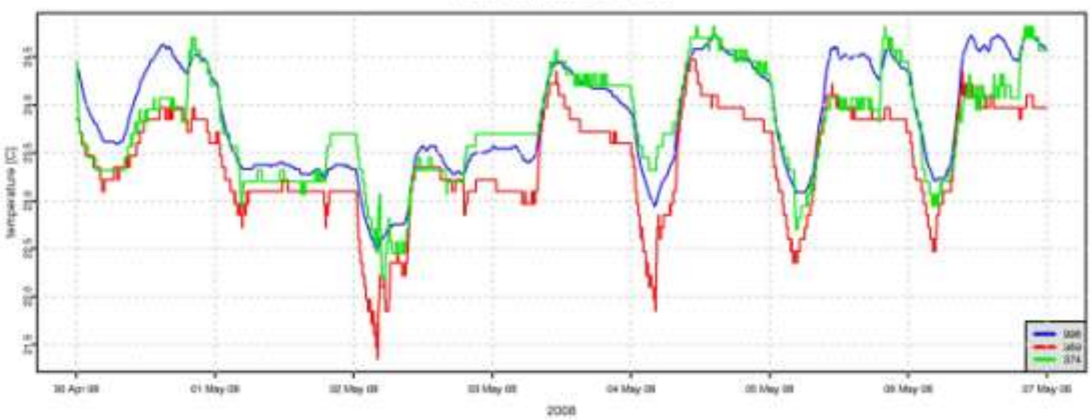
Room temperature 230



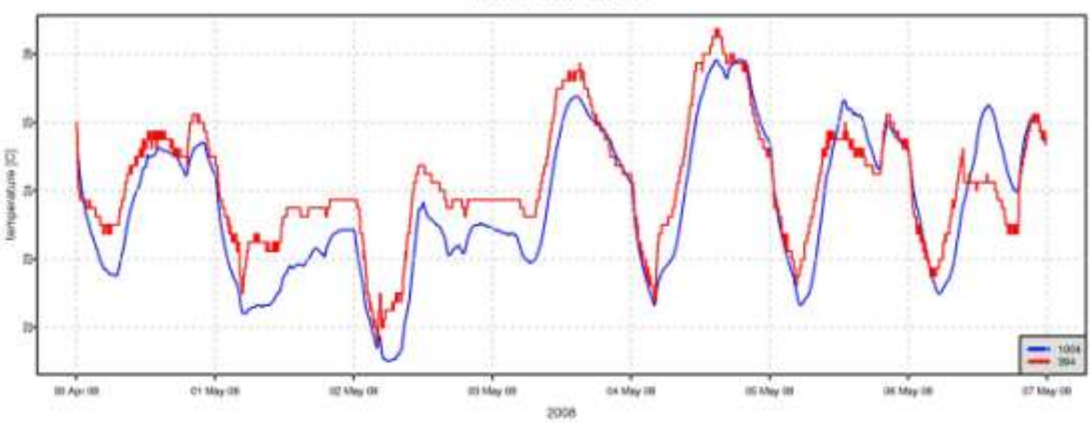
Room temperature 302

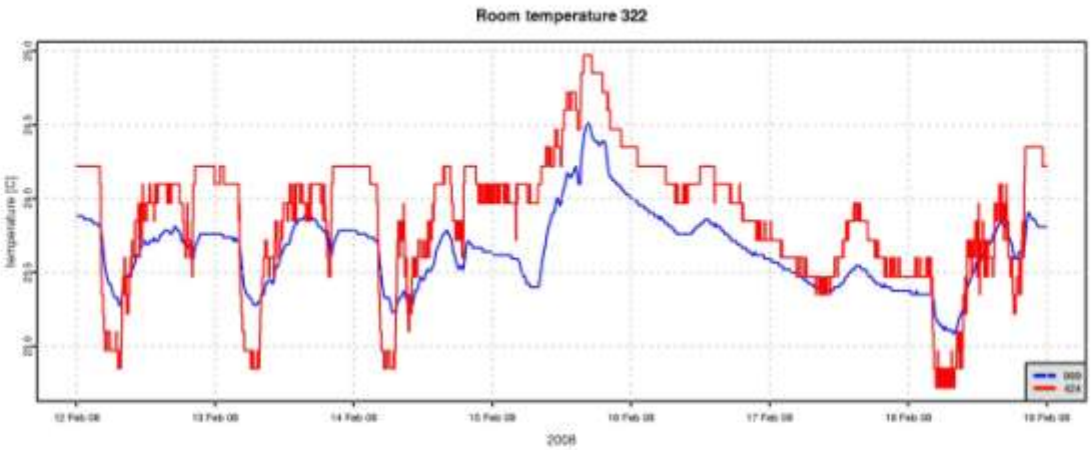


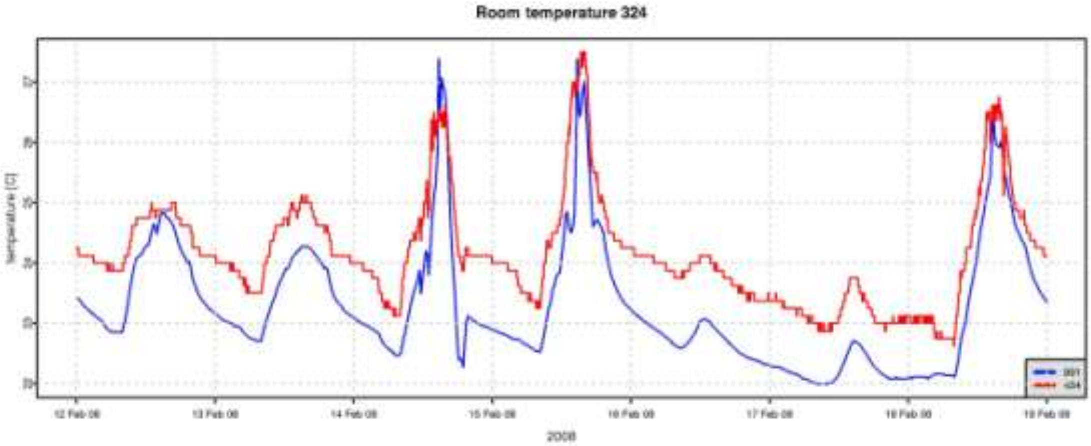
Room temperature 311-312

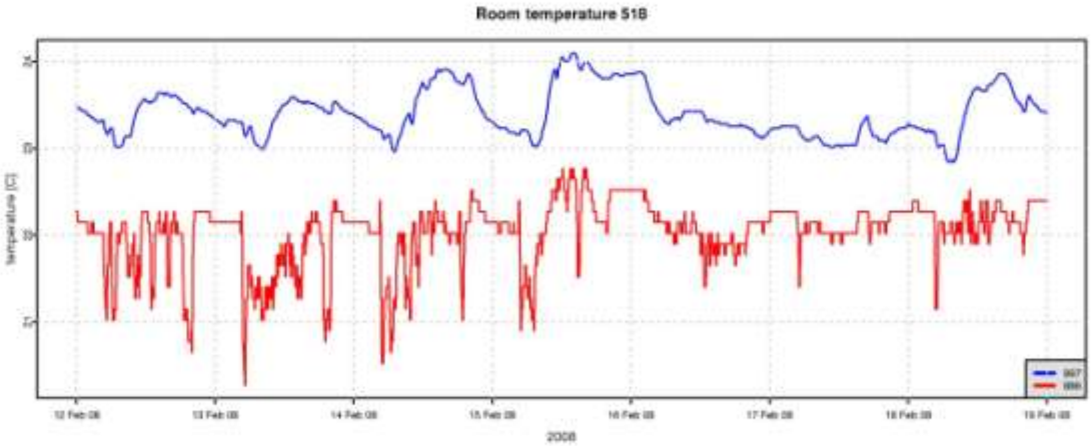


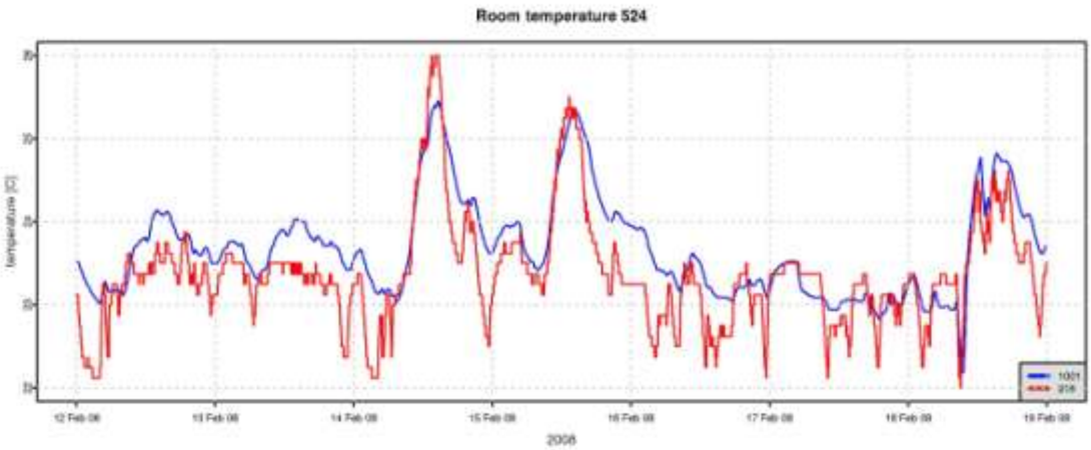
Room temperature 316

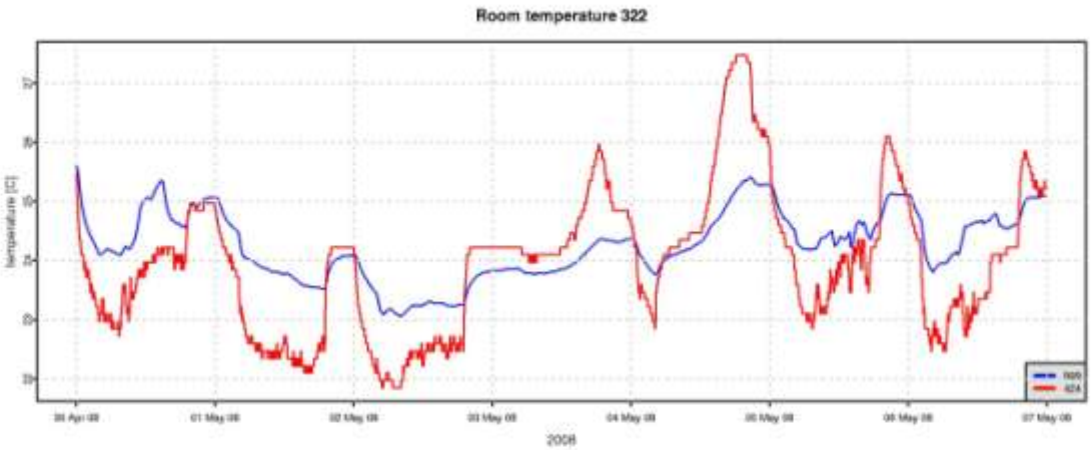


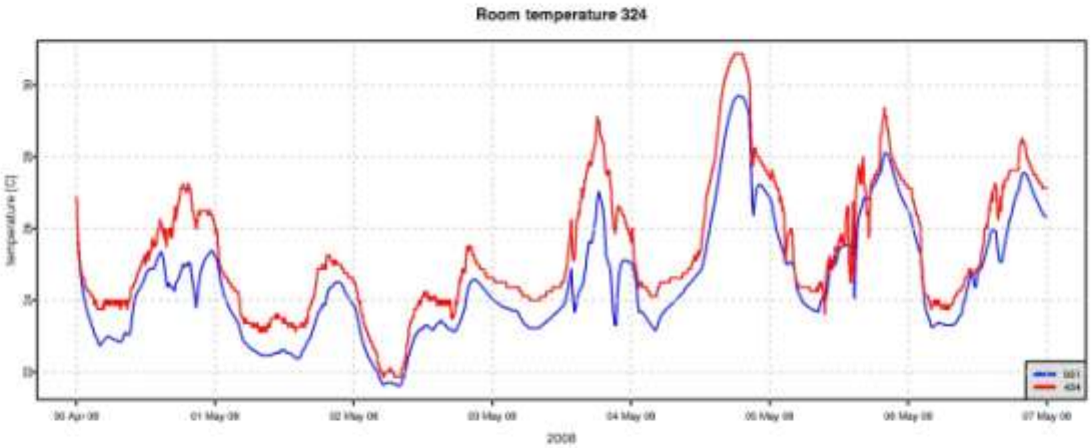

Room temperature 322
2008

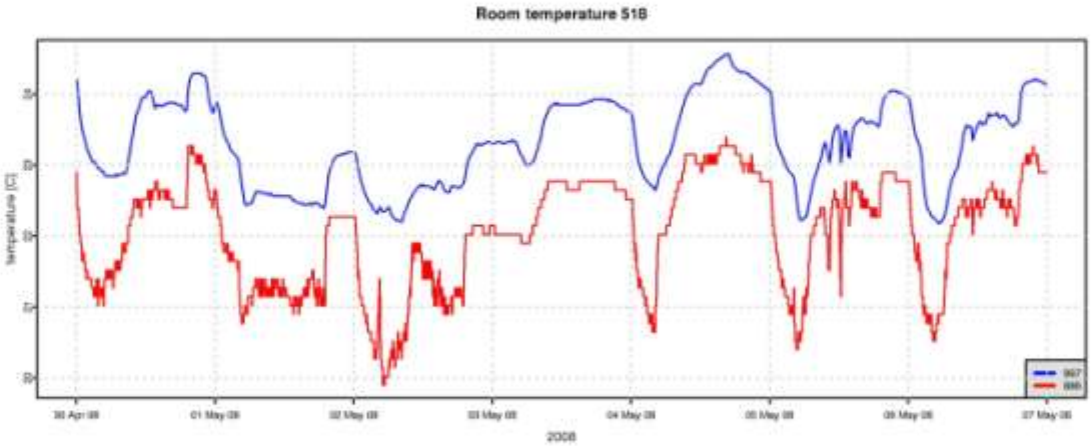

Room temperature 324
2008

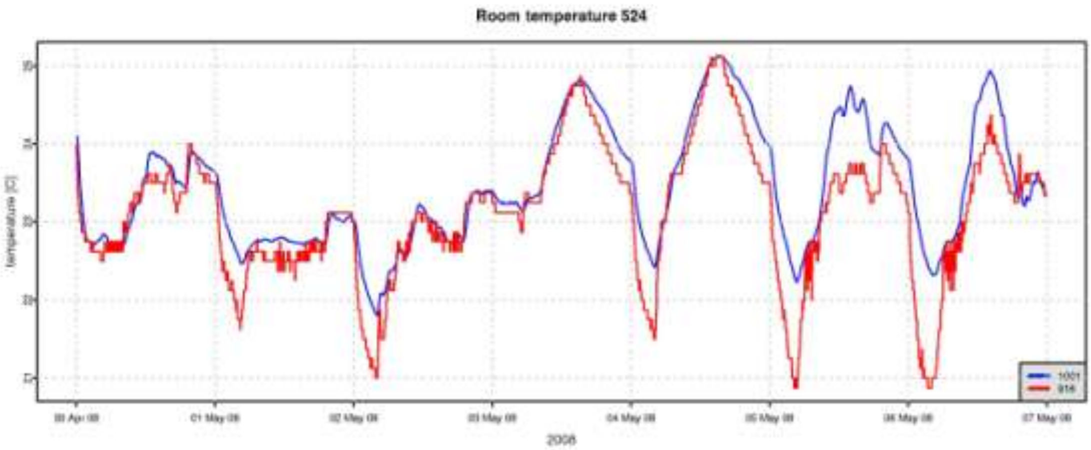

Room temperature 518
2008


Room temperature 524
2008

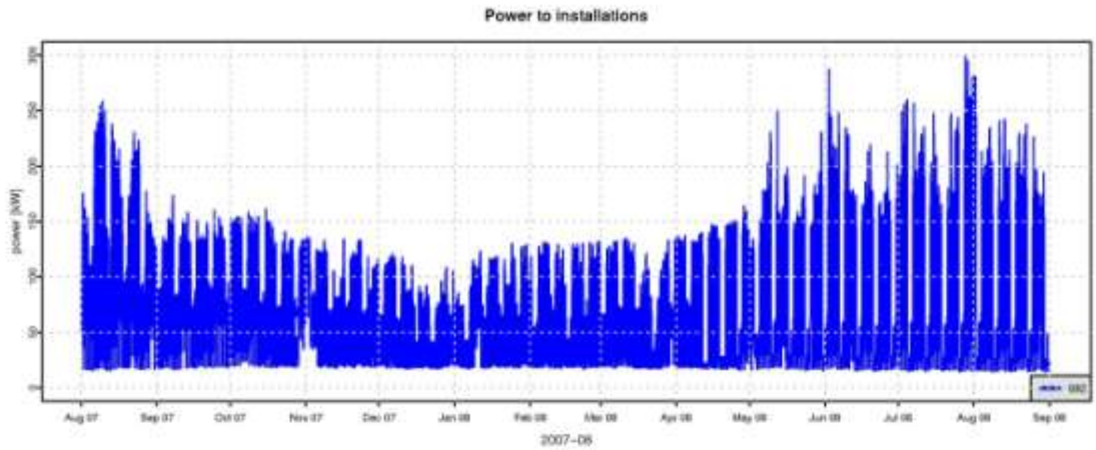

Room temperature 322
2008

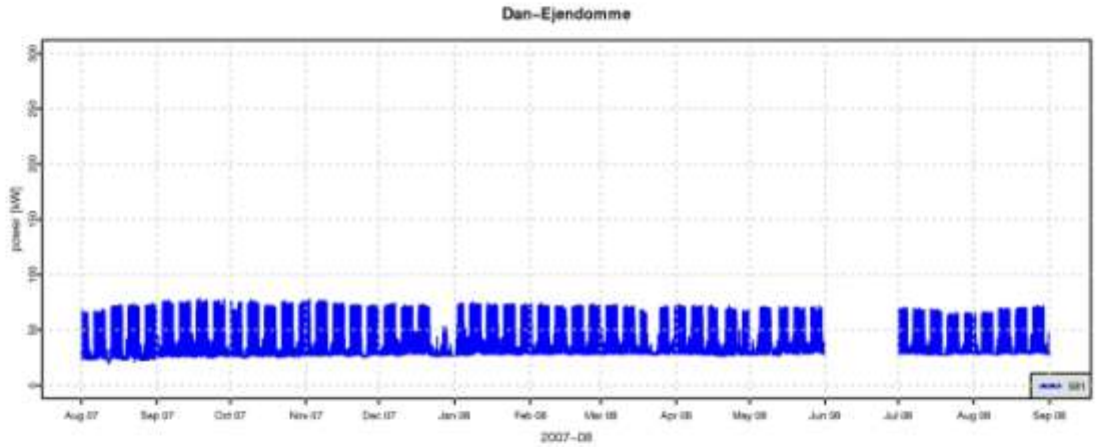

Room temperature 324
2008

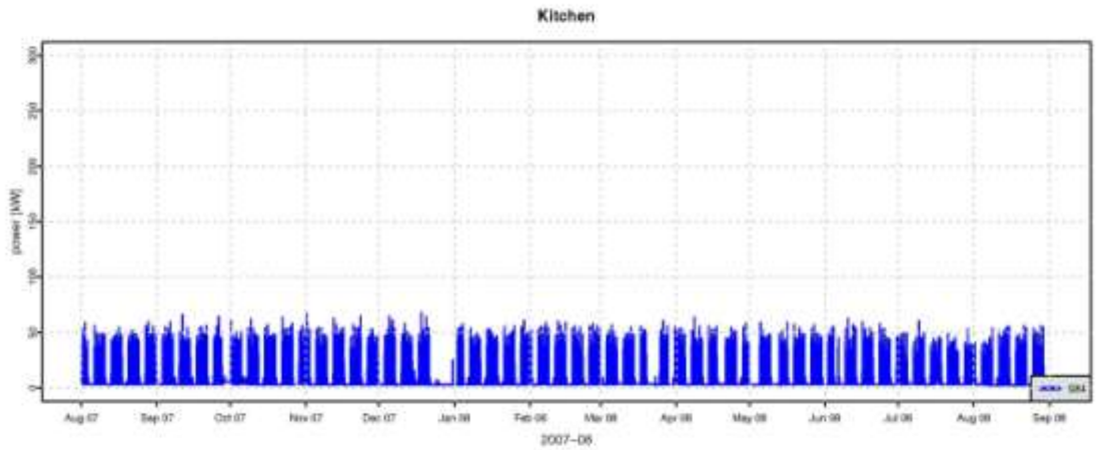

Room temperature 518
2008

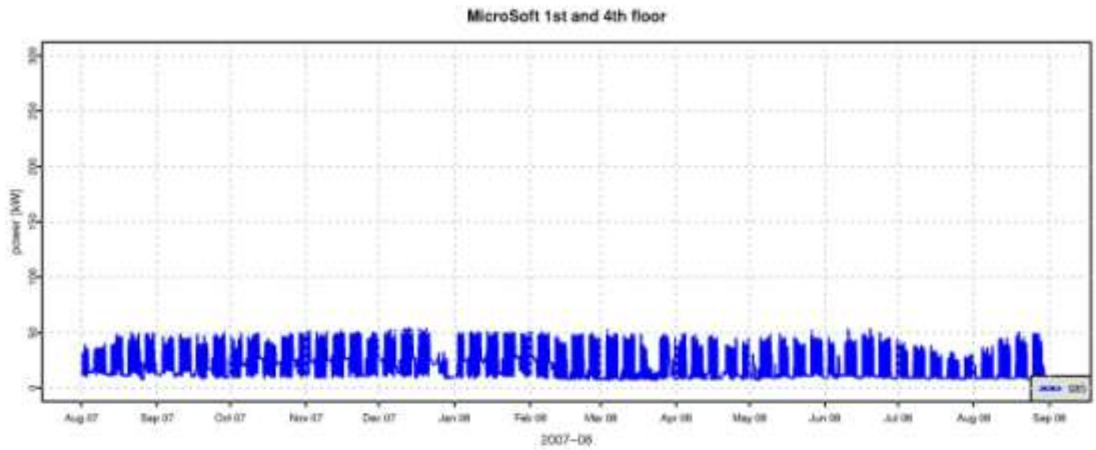

Room temperature 524
2008

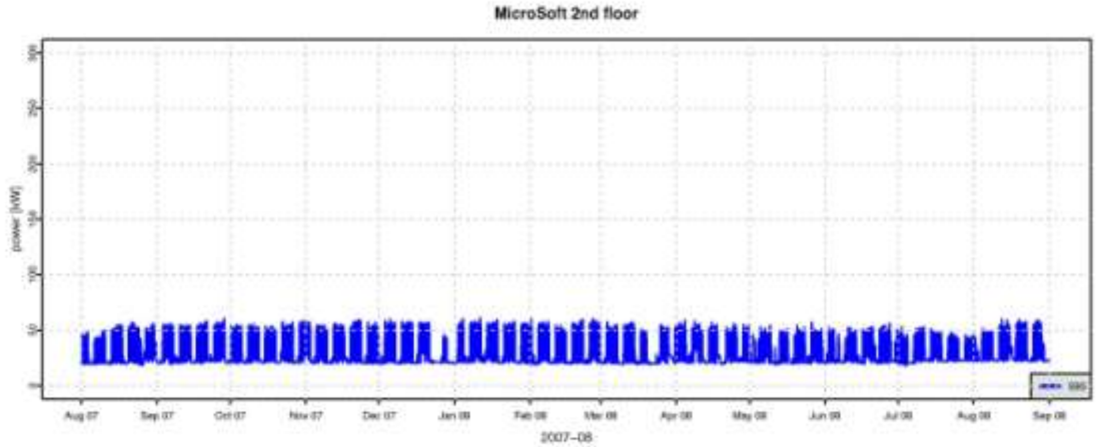
Appendix 4 Electricity demand

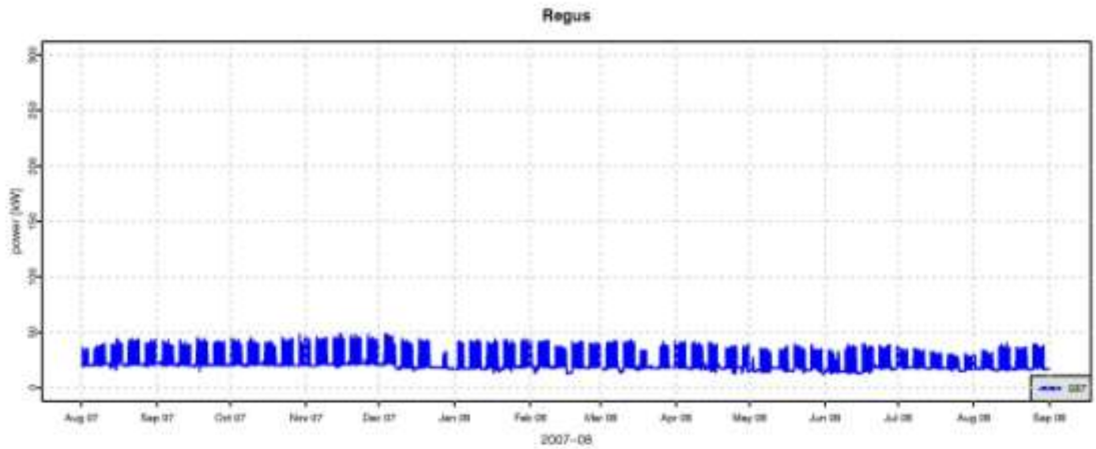




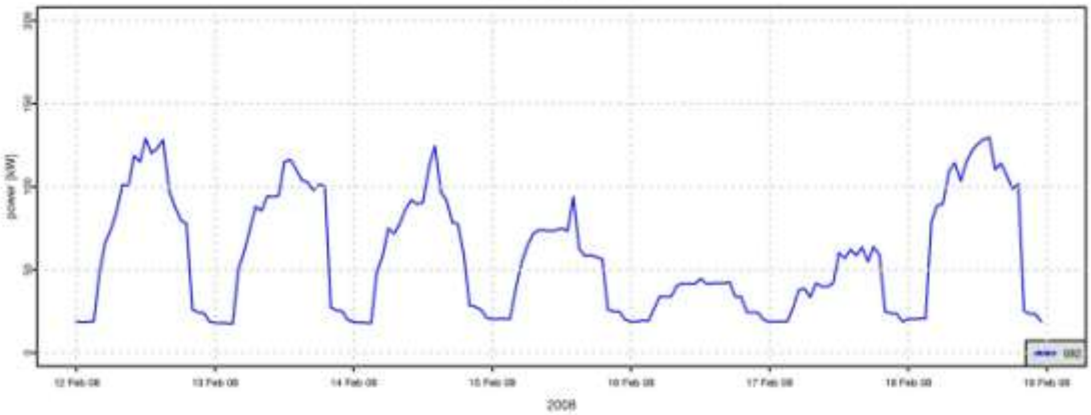



MicroSoft 1st and 4th floor
power [kW]
2007–08

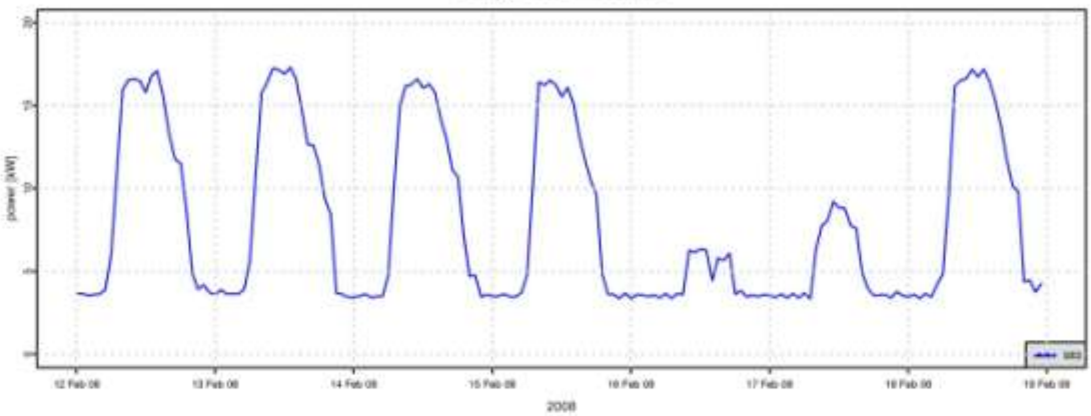

MicroSoft 2nd floor
power [kW]
2007–08


Regus
power [kW]
2007–08

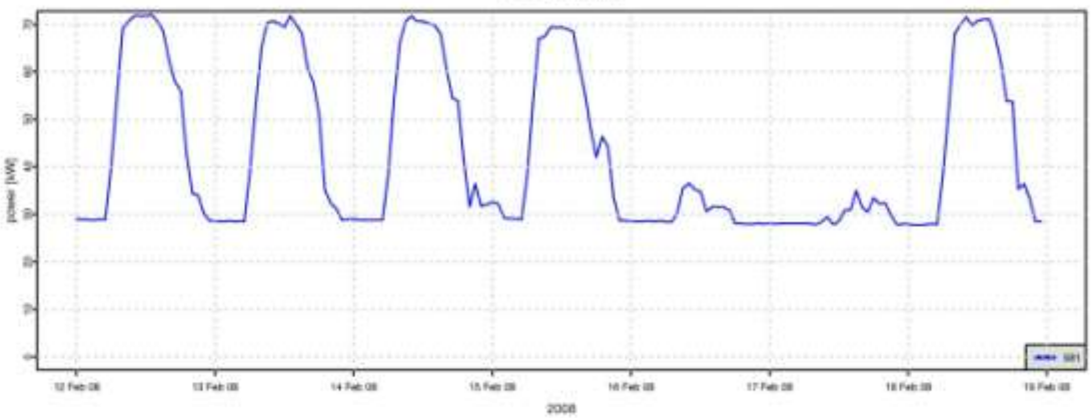
Power to installations



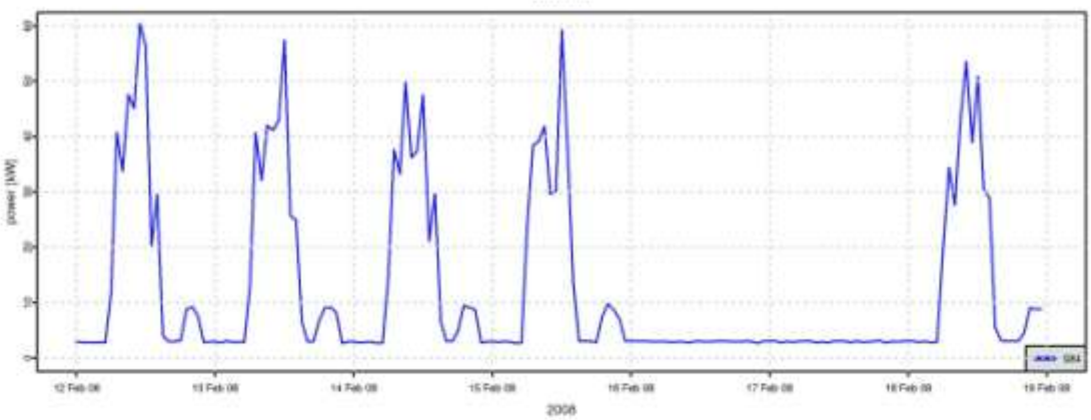
Facility manegement office



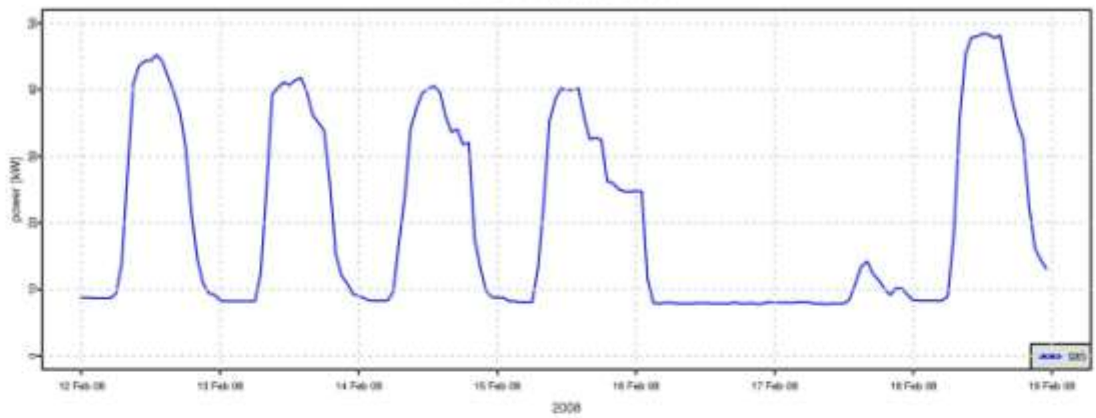
Dan–Ejendomme



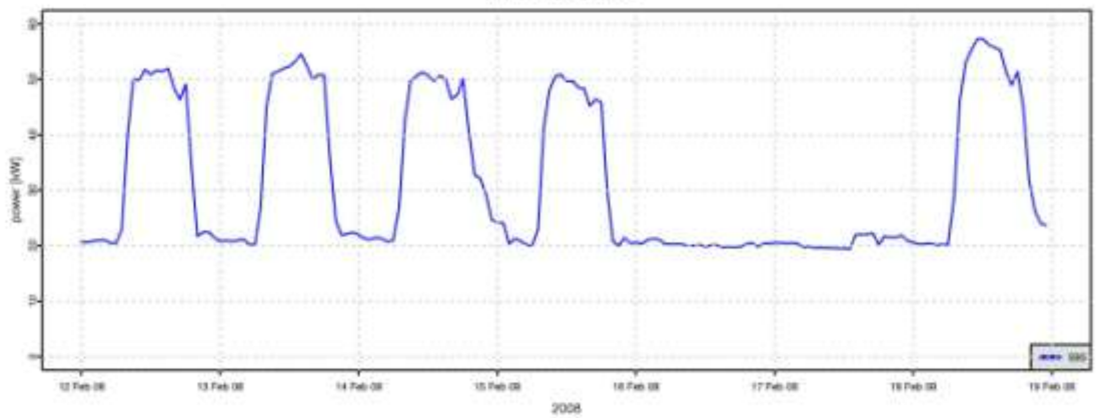
Kitchen



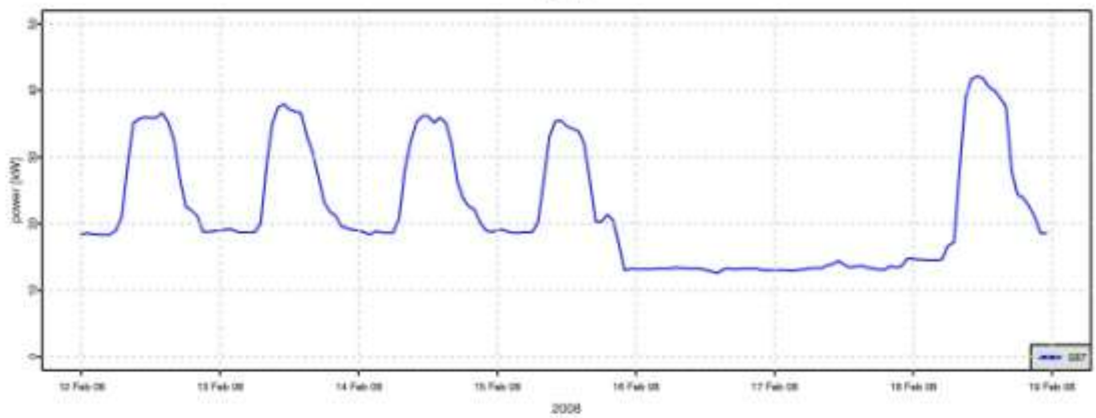
MicroSoft 1st and 4th floor

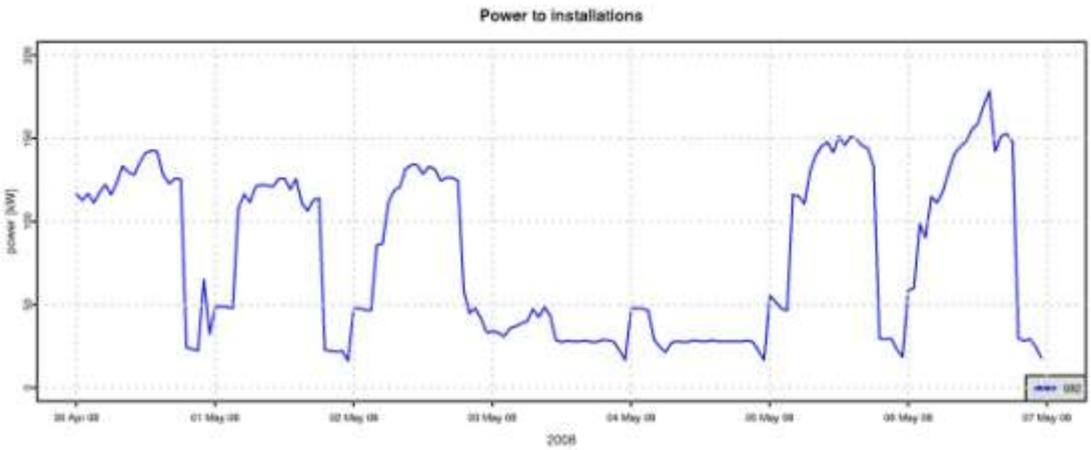


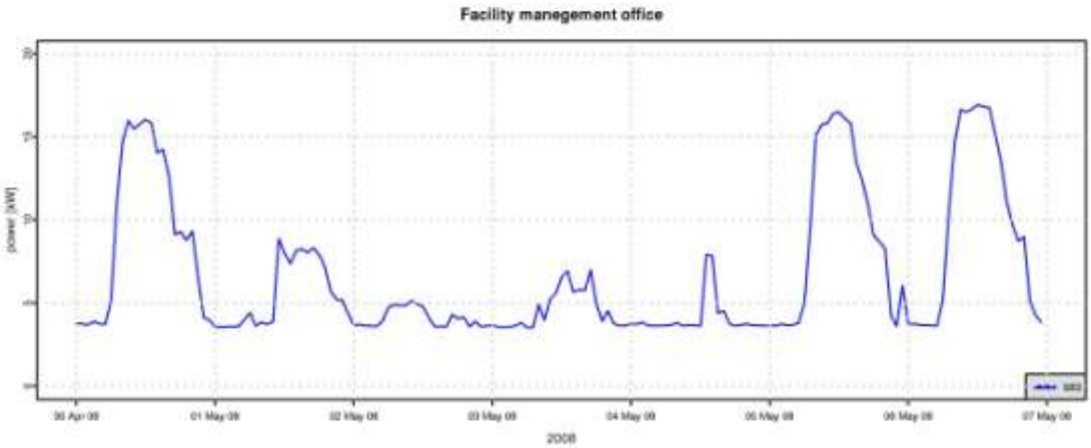
MicroSoft 2nd floor

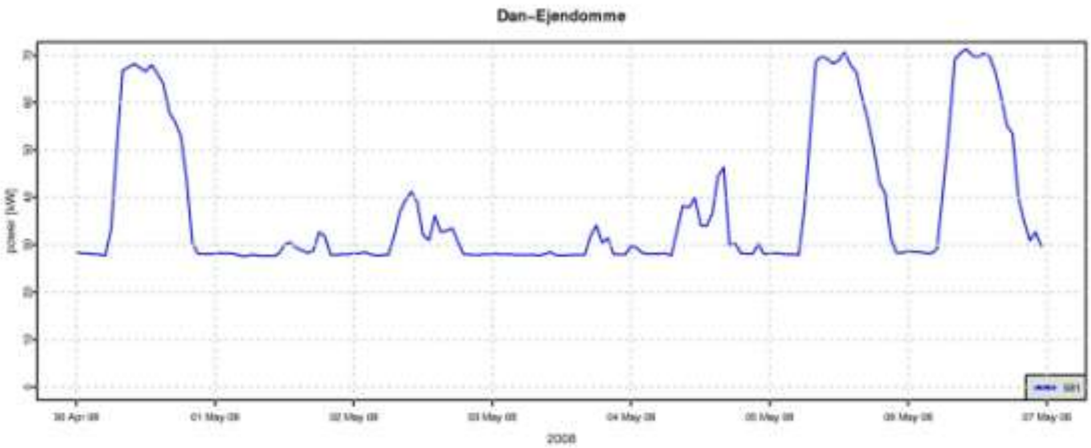


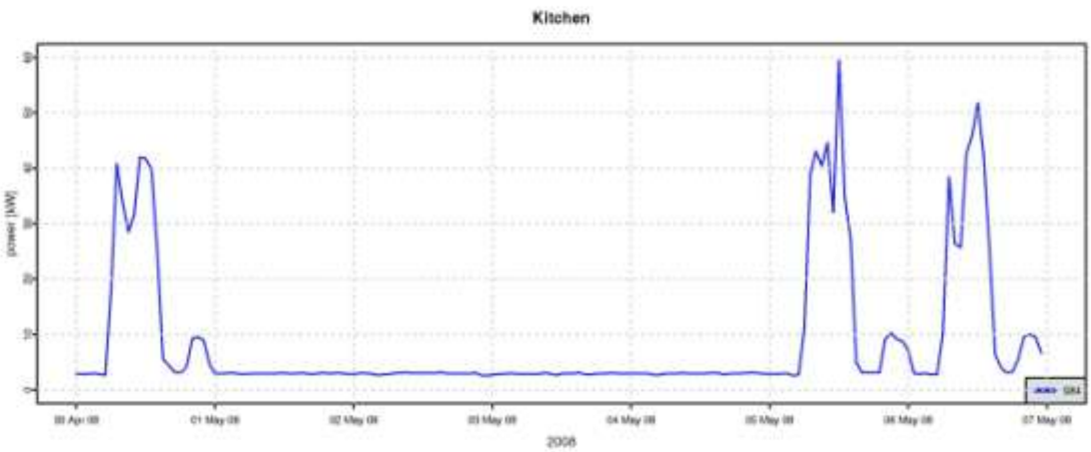
Regus



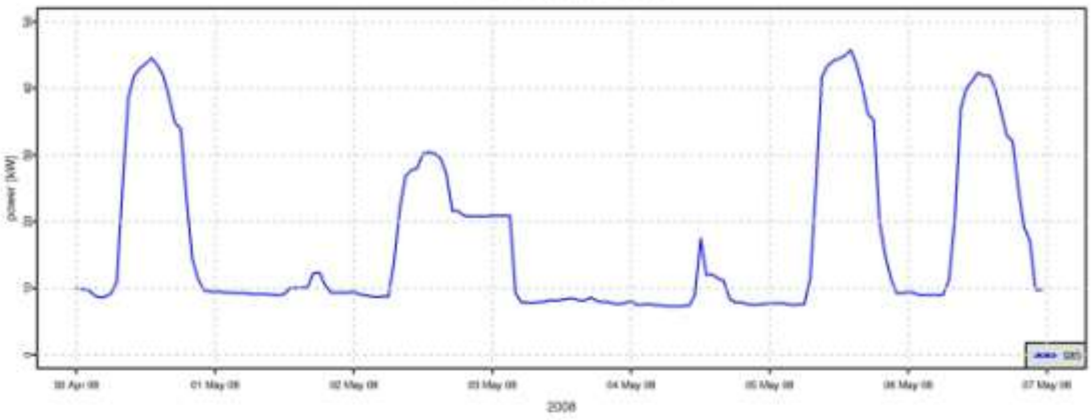

Power to installations
power [kW]
2008


Facility manegement office
power [kW]
2008

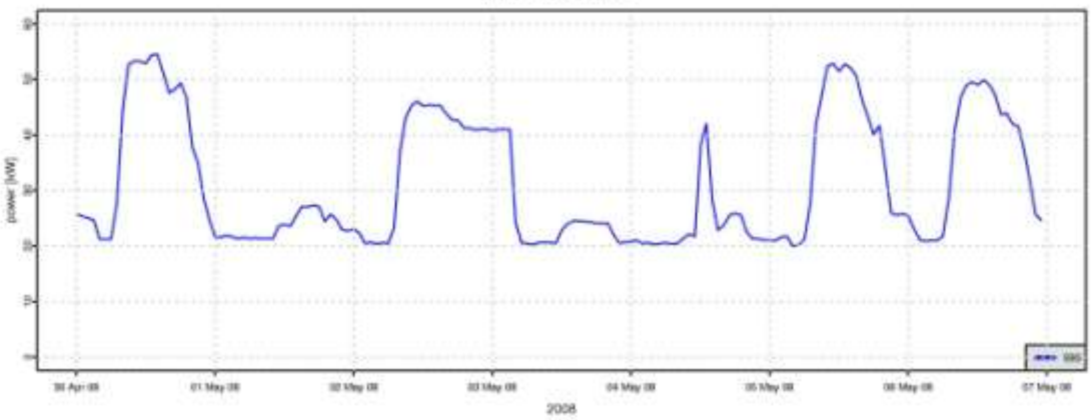

Dan–Ejendomme
power [kW]
2008


Kitchen
power [kW]
2008

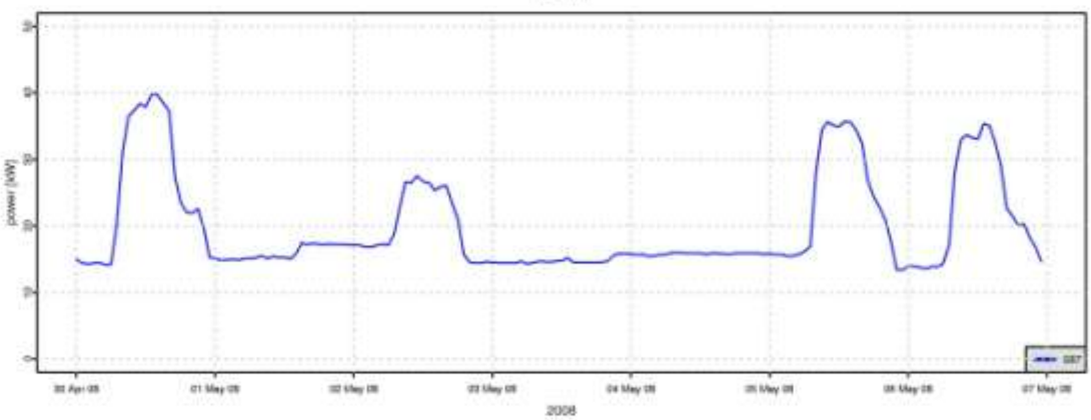
MicroSoft 1st and 4th floor



MicroSoft 2nd floor



Regus



Appendix 5 Temperatures in the rooms served by ventilation system 3

The air temperatures of the rooms serviced by Vent 3 is shown in the following graphs together with the max and min room temperatures. The max and mean room temperature are fictive temperature series logged by the BMS. The BMS logs for each time step the room temperature from the room with the highest room temperature and the lowest room temperature.

The room temperatures are arranged according to floor and if they are CAV (Constant Air Volume flow) or VAV (Variable Air Volume flow) ventilated rooms.

The max temperature is always the blue curve while the min temperature always is the red curve. The other curves are labelled with a number which is not the room number i figure 4.3 but the value number in the database. The following list translates the value number to room number – sorted in accordance to appearance in the graphs.

	value number	room number		value number	room number
CAV ground and 2nd floor	122 127 132 136 424 429 434 459	110 111 112 113 322 323 324 329	CAV 4th floor	936 941 946	531 532 533
CAV 1st floor	269 274 279 284 304 309 314	219 220 221 222 226 227 228	VAV ground and 1st floor	140 289 294 299	117 223 224 225
CAV 3rd floor	704 709 714 719 724 729 734 749	445 446 447 448 449 450 451 454	VAV 2nd floor	439 444 449 454 464 469 474 479	325 326 327 328 330 331 332 333
CAV 3rd floor	754 759 764 769 774 779 784 789	455 456 457 458 459 460 461 462	VAV 3rd and 4th floor	739 744 951 956 961	452 453 534 535 536

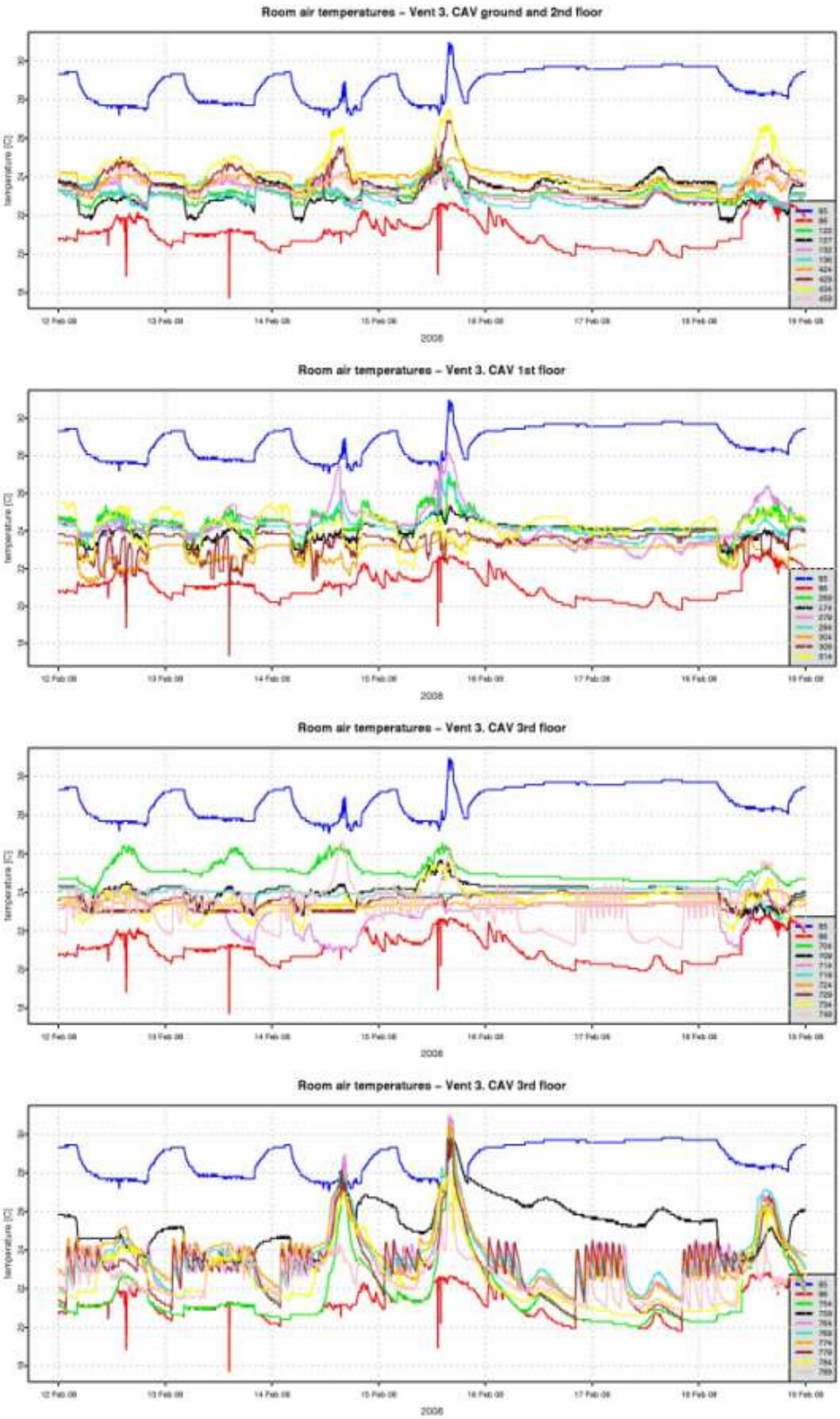

Room air temperatures – Vent 3. CAV ground and 2nd floor
Room air temperatures – Vent 3. CAV 1st floor
Room air temperatures – Vent 3. CAV 3rd floor
Room air temperatures – Vent 3. CAV 3rd floor
2008

Figure A5.1.

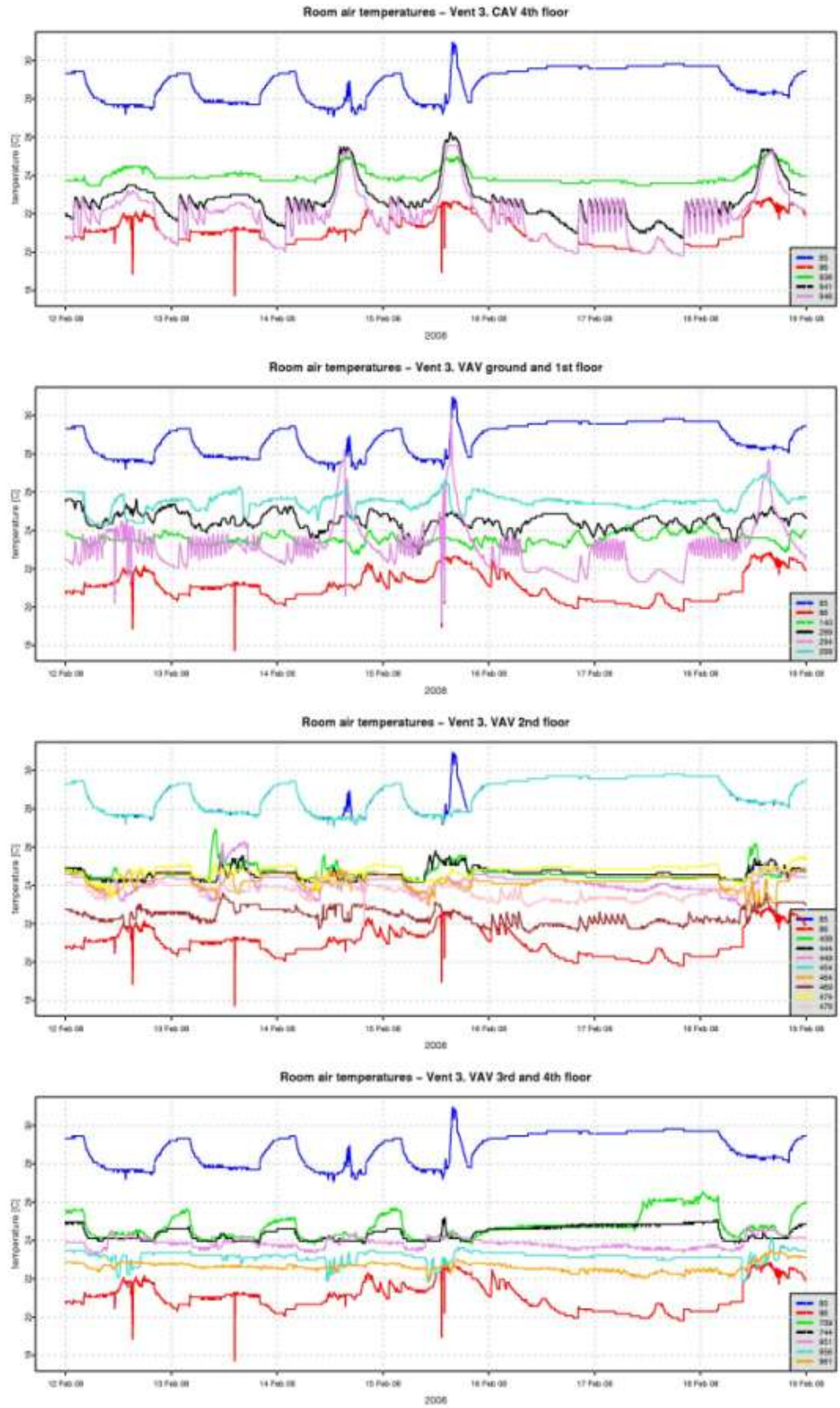

Room air temperatures – Vent 3. CAV 4th floor
2008
Room air temperatures – Vent 3. VAV ground and 1st floor
2008
Room air temperatures – Vent 3. VAV 2nd floor
2008
Room air temperatures – Vent 3. VAV 3rd and 4th floor
2008

Figure A5.2.

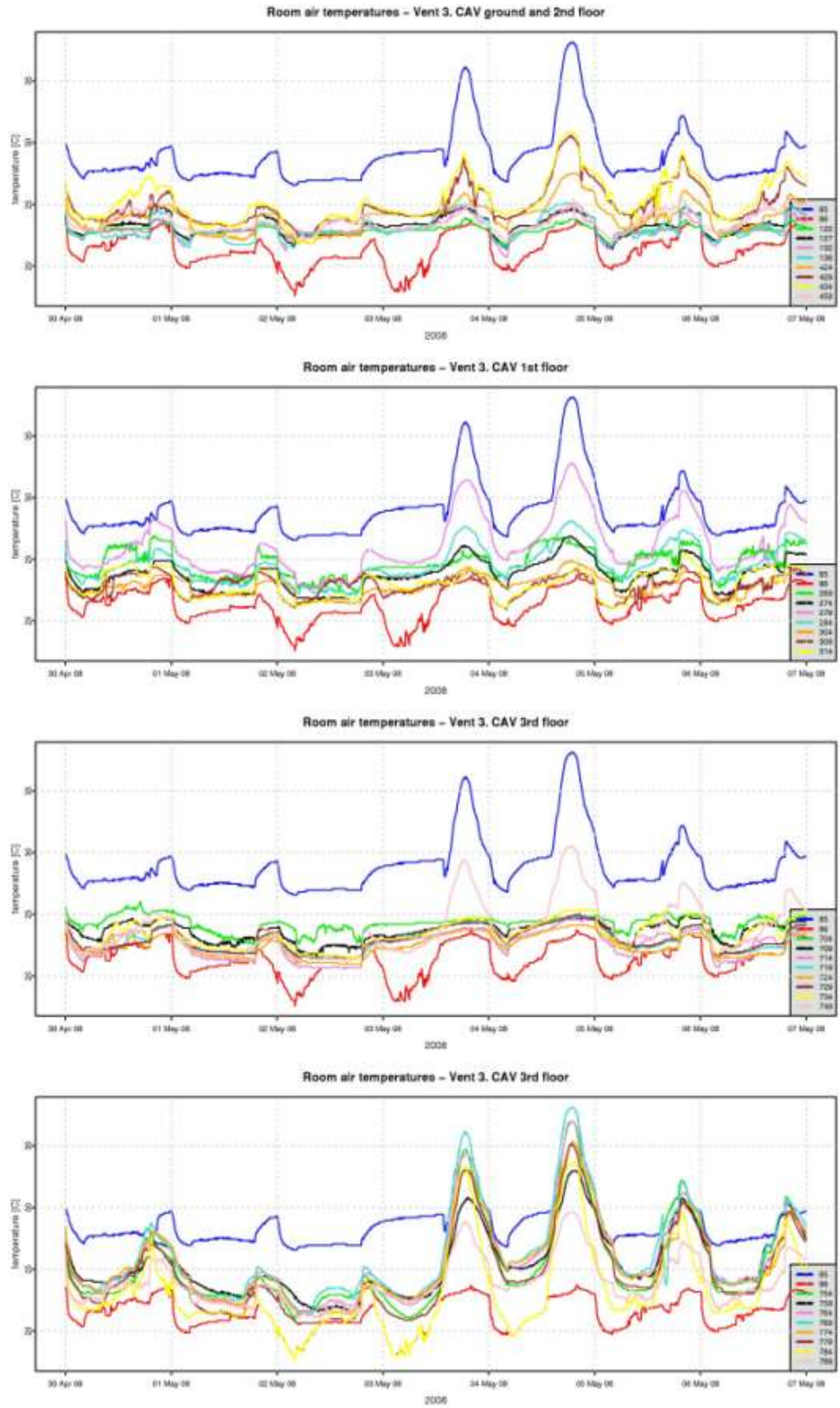

Room air temperatures – Vent 3. CAV ground and 2nd floor
temperature [C]
2008
Room air temperatures – Vent 3. CAV 1st floor
temperature [C]
2008
Room air temperatures – Vent 3. CAV 3rd floor
temperature [C]
2008
Room air temperatures – Vent 3. CAV 3rd floor
temperature [C]
2008

Figure A5.3.

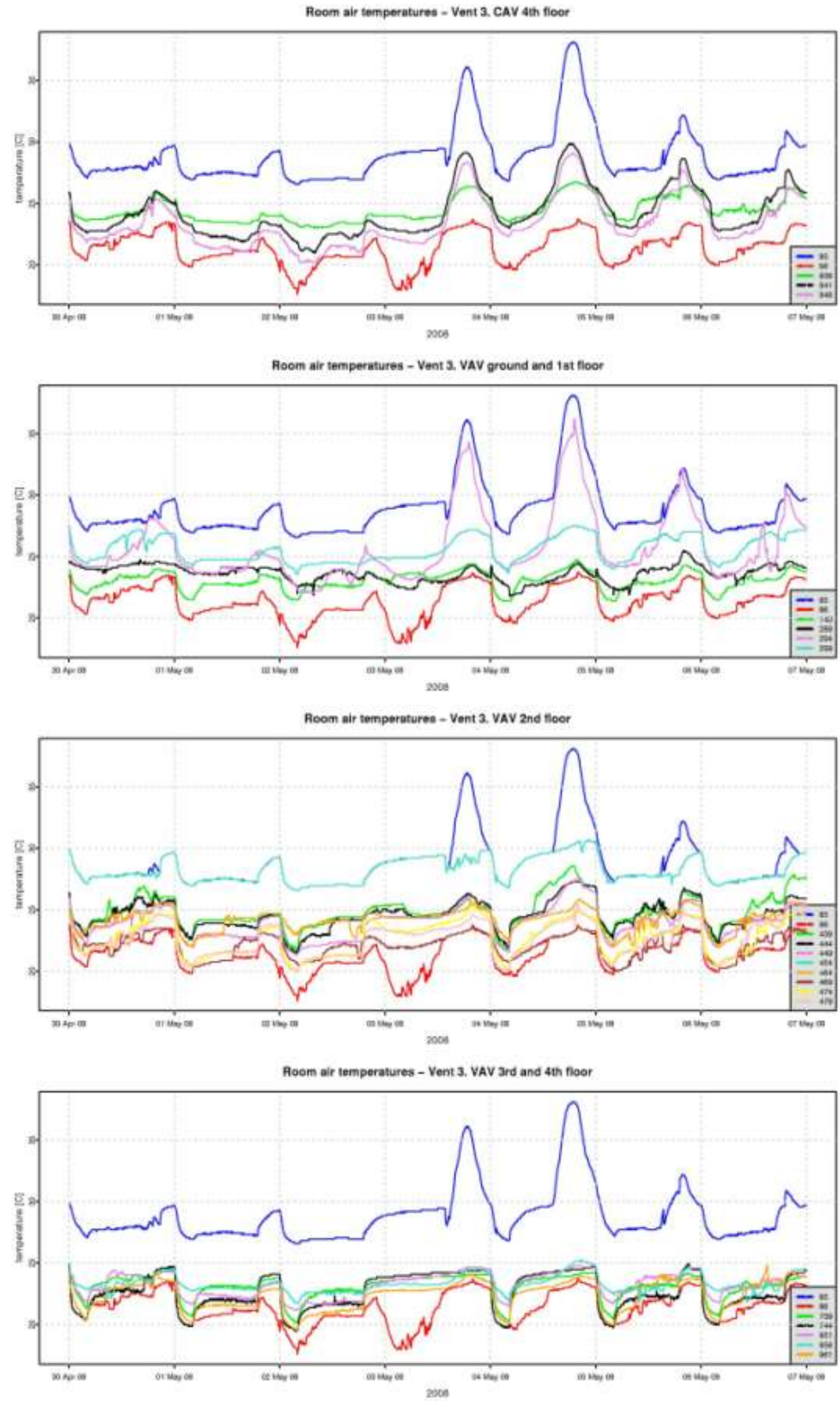

Room air temperatures – Vent 3. CAV 4th floor
2008
Room air temperatures – Vent 3. VAV ground and 1st floor
2008
Room air temperatures – Vent 3. VAV 2nd floor
2008
Room air temperatures – Vent 3. VAV 3rd and 4th floor
2008

Figure A5.4.

Appendix 6 Introduction to R and MySQL

Along with the increasing volume of data that one acquires and stores, combining relational databases and scientific software is gaining popularity. It makes working with large data sets easier. In the Multiparameter controllers project, the data to be investigated were stored in a MySQL type database (www.mysql.com). MySQL is an open source database management system. To make sure that all users would access and work on the same version of the database (preventing potential updates taking place with delay as experience in the early stage of this project), it was commonly agreed that the database would be hosted on a server at the department of Informatics and Mathematical Modelling (IMM) of DTU. Users could access it through special IMM accounts which were created for the purpose of this project.

However, MySQL is mainly used to optimize data storage and retrieval rather than to display and analyze them. Therefore, users needed a complementary environment whose features would allow to connect to the database, extract data, generate high quality graphics and provide a collection of functions to perform mathematical and statistical analysis. Due to the lack of speed and limited statistical capabilities of Excel, the statistical and open source environment R (http://cran.r-project.org/) was a natural choice. Although many tasks which used to be performed using relational databases can easily and entirely be implemented in R nowadays, the present chapter of this report will show that there are still some situations where combining the respective power of MySQL and R nicely enhances their respective capabilities.

There are two common ways to connect R to databases. The first one uses the ODBC (Open DataBase Connectivity) facility available on many computers. The second one uses DBI package of R along with a specialized package for the particular database that one wants to access. Common rules state that:

- if one uses a database for which a specialized package is not available, using ODBC may be the only option.
- if there is a specialized package available for the database used, the corresponding DBI-based package may outperform the Open DataBase Connectivity (ODBC) approach.

Due to its easiness of implementation and to the database type, the second approach was chosen in this project. The corresponding DBI-based package used is called *RMySQL*.

The present appendix was largely inspired by (Spector, 2008).

A6.1. The SQL syntax in MySQL

The Structured Query Language (SQL) is a database language used to manipulate data: to retrieve, insert, delete and update stored data.

A6.1.1. Data structure in a database

Since a single server may host more than one database each with potentially many tables, and since each table can contain many fields (variables), it may be useful to examine exactly what is available in a database before starting to work with it. Table A6.1 shows some common tasks and the related SQL statements to execute them:

Task	SQL Query
Find the names of available databases	SHOW DATABASES;
Find the table names in a database	SHOW TABLES IN database_name;
Find the field names in a table	SHOW FIELDS IN table_name;
Find the types of fields in a table	DESCRIBE table_name;
Change the default database	USE database_name;

Table A6.1. A few SQL commands

When using command-lines, each SQL statement must end in a semi-colon but this is not required when using the *RMySQL* interface.

A6.1.2. Basics of SQL

When starting with SQL, one has to keep in mind that, unlike R, it is not a programming language; operations in SQL are performed using individual queries without loops or control statements. The main and therefore most used SQL command is *SELECT*. Queries are performed using single statements. As a result, the syntax of the *SELECT* command can be quite long:

```
SELECT field_name
FROM table_name
WHERE condition_1
GROUP BY field_name
HAVING condition_2
ORDER BY column (ASC | DESC)
LIMIT offset, count;
```

Fortunately, most of the clauses in the *SELECT* statement are optional. In fact, many queries will simply retrieve all the data in a particular table through the following command:

```
SELECT * FROM table_name;
```

The asterisk (*) means “all the fields in the table”. Alternatively, a comma-separated list of fields or expressions can be supplied:

```
SELECT field_1, field_2, ...
FROM table_name_1, table_name_2, ... ;
```

A6.1.3. Modifying Database records

Although there are many SQL commands to manipulate data stored in relational databases, we give special focus on the following ones: *UPDATE*, *DELETE* and *DROP*. They allow modifying database records. It is worth noticing that these commands take effect on the database as soon as they are issued, so it is a good idea to have a backup of the data in another database before using them. But since no backup was possible on the SQL server at IMM (at least in the beginning), these commands were not used extensively in the present project but could turn out to be very useful for other projects. To change the values of selected records in a database, the *UPDATE* command can be used. The format of the *UPDATE* statement is:

```
UPDATE table_name SET var=value
WHERE condition;
```

To change more than one field's value, the *field=value* specification can be replaced with a comma-separated list of field/value pairs. To completely remove a record, the *DELETE* statement can be used. The basic syntax is as follows:

```
DELETE FROM table_name
WHERE condition;
```

Without a *WHERE* clause, all of the records of the database will be removed, so this statement should be used with caution. To completely remove an entire table or database, the *DROP* statement can be used:

```
DROP TABLE table_name;
```

or

```
DROP DATABASE database_name;
```

When using the *DROP* command, an error will be reported if the table or database to be dropped does not exist. To avoid this, the *IF EXISTS* can be added to the *DROP* statement as in:

```
DROP DATABASE IF EXISTS database_name;
```

A6.2. Connecting R and a database

As mentioned previously, there are two main ways of accessing the data stored in a relational database through R.

A6.2.1. The ODBC facility

The first one consists in using the ODBC facility and it can apply to almost any type of databases. Even though this approach was not used in the present project, it is worth mentioning it for future projects with large data sets. This facility allows to access to a variety of databases through a common interface. In R, the *RODBC* package, available from CRAN (http://cran.r-project.org/web/packages/), is used to access this capability. ODBC was originally developed on Windows, and the widest variety of ODBC connectors will be available on that platform. However, both Linux and Mac OS X also provide database connectivity through ODBC. If one needs to use a database in R which is not directly supported, *RODBC* will probably be the best choice, as many database manufacturers provide ODBC connectors for their products. The first step in using *RODBC* is to set up a DSN (Data Source Name). It is a file which is configured to provide all the necessary information to connect and access the database: server, username, password, and database name. The second step consists in loading the *RODBC* package from the R environment and creating a connection by simply passing the DSN to the R *odbcConnect()* function as follows:

```
> library(RODBC)
> con=odbcConnect("dsn_filename")
```

Additional keywords defining the connection can be provided in the DSN inputs: server, user, password, port and database. For instance:

```
> con=odbcConnect("dsn_filename",pwd="xxxx",user="immpjt")
```

Once the user has got a connection to the ODBC source, the *sqlQuery()* function allows any valid SQL query to be submitted. This will be the case even if SQL is not the native language of the underlying database. To prevent unnecessary resource use, the *odbcClose()* function should be passed to close any ODBC connection objects when they are no longer needed.

A6.2.2. The DBI-based package

The approach presented on this subsection is more specific than the RODBC approach. Combining R and MySQL is getting more and more popular since both run on a variety of platforms and are relatively easy to configure and operate. Accessing a MySQL database from the R environment requires to load the *RMySQL* package. This package will automatically load the required *DBI* package, which provides a common interface across different databases. Then, the MySQL driver is loaded via the *dbDriver()* function, so that the DBI interface will know what type of database it is communicating with:

```
> library(RMySQL)
> drv= dbDriver("MySQL")
```

The specifications of the database connection can then be provided through the *dbConnect()* function. These include the database name, the database username and password, and the host on which the database is running. If the database is running on the same machine as the R session, the hostname can be omitted. For example, to access a database called “bldg_th”, via a user name of “TI_user” and a password of “xxxx” on the host “pjtsqlsrv.imm.dtu.dk”, the following call to *dbConnect()* could be used:

```
> con=dbConnect(drv,dbname="bldg_th", user="TI_user", password="xxxx",
                       host="pjtsqlsrv.imm.dtu.dk")
```

The calls to *dbDriver()* and *dbConnect()* need only to be made once for an entire session. One can close an unused DBI connection object by calling *dbDisconnect()*. SQL queries make requests for some or all of the variables in one or more database tables. In most cases, a single call to *dbGetQuery()* can be used to send a query to the database. For instance:

```
> data=dbGetQuery(con,"SELECT * FROM table_name")
```

Any valid SQL query can be passed to a database by this method.

A6.3. An example on how to combine a relational database and R

In studies involving large data sets, it is often more convenient to look at data plots than data tables when suitable graphical tools are available, for many reasons. First, it gives a broad overview on the types of data to be investigated. Then, it easily enhances specific insights into the data. At last, it can allow oneself to better identify dependency structures in the data.

For the purposes of the Multiparameter controllers project, we developed a collection of functions available from the R environment. These functions mainly consist in graphical tools and a few of them give statistical summaries of the data. A tutorial on how to use these functions is given in Appendix 7.

Appendix 7 A tutorial on R and tools to visualize data

This tutorial provides a brief introduction to R (www.cran.r-project.org) and some R functions developed to visualize data and export graphics in the framework of the Multiparameter Controllers project.

Since the programs are running in connection with a copy of the database hosted on a server at IMM-DTU, one first needs to log on to the IMM server via the ThinLinc client which is used to virtualize desktops. The application file to install it can be freely downloaded at www.cendio.com.

A7.1. Log on the IMM server

Figure A7.1. ThinLinc client login.

Once the ThinLinc Client has been installed and started (the startup interface can be seen in figure A7.1), the user must enter:

- the server name: thinlinc.imm.dtu.dk
- a name/login
- a password

It takes a few seconds to log on to the IMM-DTU server. If everything works correctly, a window virtualizing a UNIX desktop environment is opened (see figure A7.2). The user can easily switch from the virtual UNIX desktop to the desktop of his current operating system by pressing the windows key on his keyboard and then minimizing the virtual window or by turning the "full screen" mode off (see figure A7.3).

Figure A7.2. Unix desktop environment.

Figure A7.3. Minimizing the Unix session.

The user accounts relevant to the project have been equipped with a folder called *MultiParamContr* (see figure A7.4). It contains different sub-folders with different purposes. One is called “common” and is maintained by Pierre-Julien and Philip. Do not save anything in it since you will probably lose it when the directory is updated. In the *common/doc* folder you will find the documentation related to the project (this tutorial, descriptions of data, etc).

Figure A7.4. The folder used for the Multiparameter Controllers project.

To reach the file system at IMM from a Windows PC, one can use WinSCP (www.winscp.net). It's an easy-to-use client, similar to many FTP clients. Connect to thinlinc.imm.dtu.dk with the same login as when using ThinLinc.

A7.2. Starting R

It is straight forward to start R. First, the user opens a *hms1* terminal window in the list of available terminal windows (see figure A7.5).

Now, in the *hms1* terminal window, type *Rmultiparam*. This a script made to set up the necessary environment to work with the data and R functions created for that. The command will result in both opening the file the user uses to save his command lines (in a separate window) and starting R (see figure A7.6).

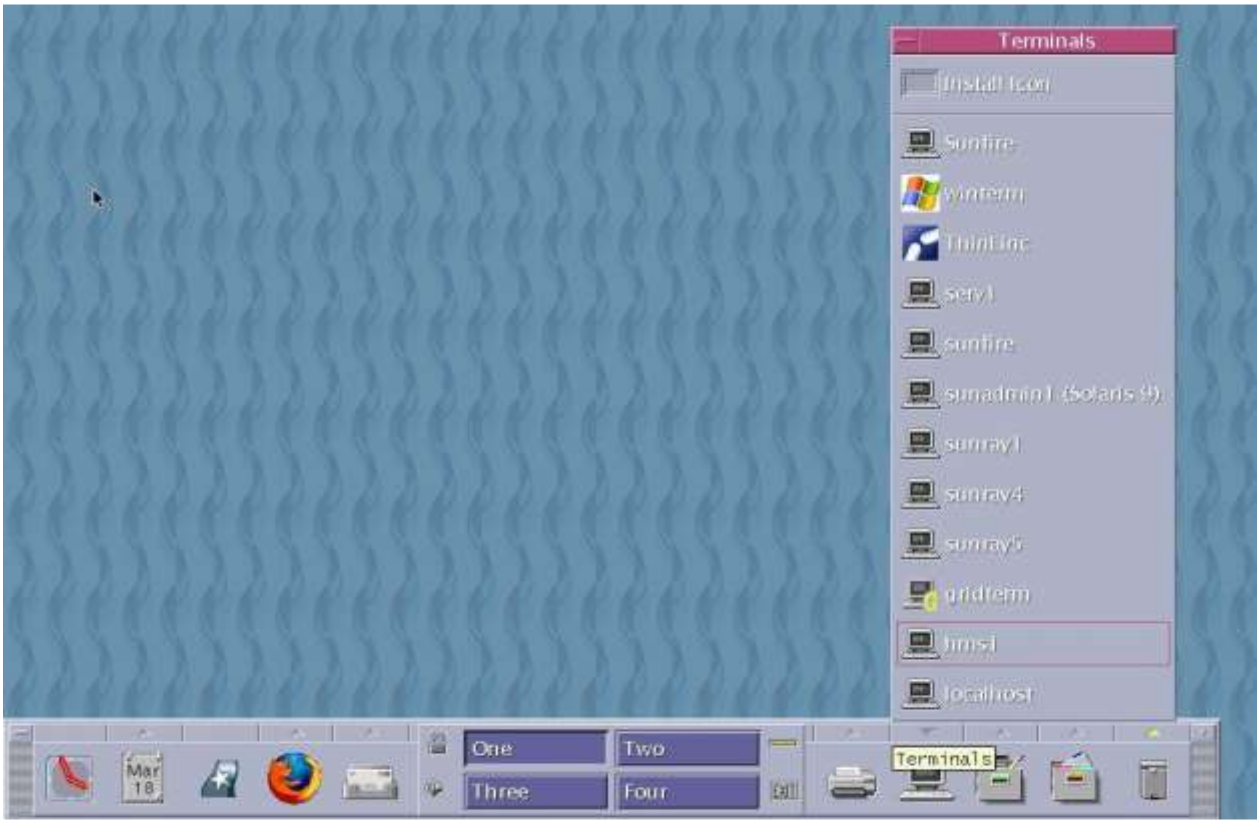


Figure A7.5. Starting a terminal. Notice that it must be on *hms1*.

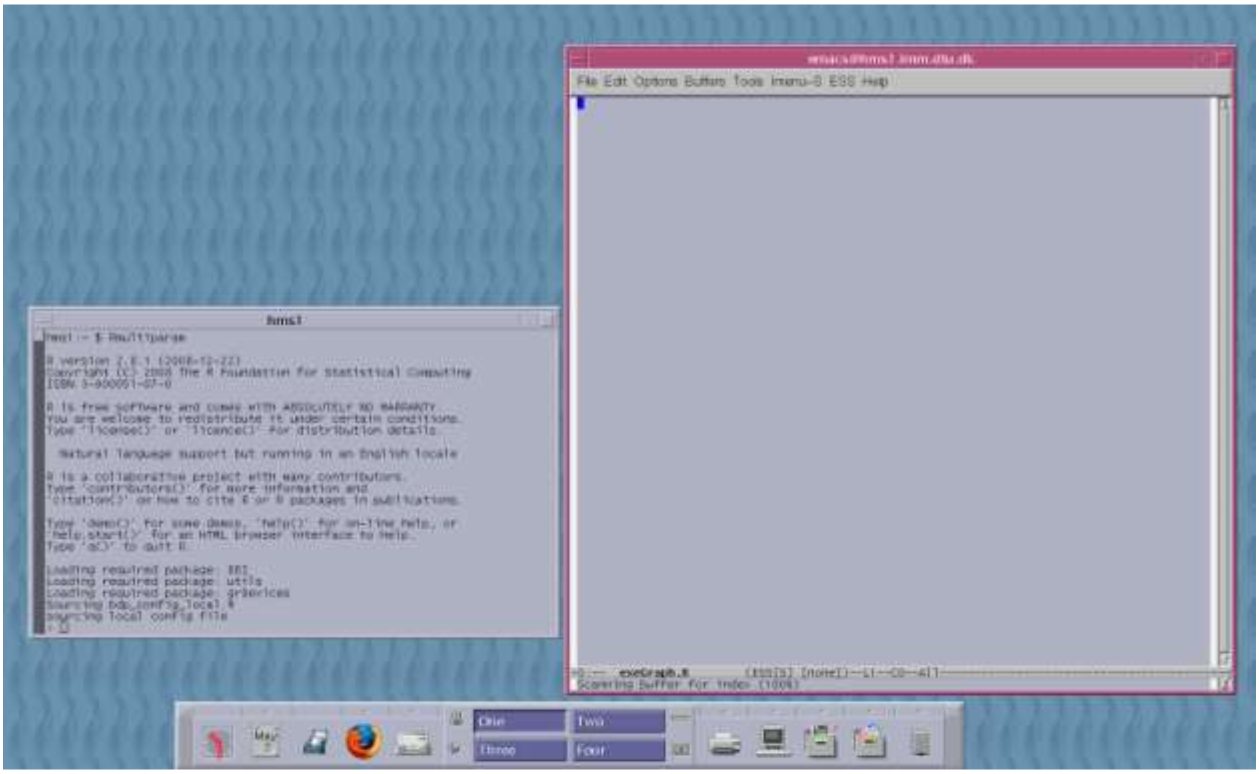


Figure A7.6. R is launched with the *Rmultiparam* command taking care of the initialization.

A7.3. The R interface

R is an advanced collection of software for numeric mathematical modelling and statistics. It can produce graphics of very high quality. To get started with R, one can have a look at one or more of the following:

- http://cran.r-project.org/doc/manuals/R-intro.html
- http://cran.r-project.org/doc/contrib/Owen-TheRGuide.pdf
- http://cran.r-project.org/doc/contrib/Verzani-SimpleR.pdf

Technically, R is an expression language which means that the user has to write command lines to call functions and to create object/variables. If a command is not complete at the end of a line, R will give a different prompt (instead of the usual ">"), by default "+" on second and subsequent lines and continue to read input until the command is syntactically complete.

Remark: R provides a mechanism for recalling and re-executing previous commands. The vertical arrow keys on the keyboard can be used to scroll forward and backward through a command history. Once a command is located in this way, the cursor can be moved within the command using the horizontal arrow keys, and commands can be modified.

To create a vector, one can use the *c()* function. For instance:

```
> c(2,5,6)
[1] 2 5 6
```

There are 2 ways to define a sequence of numbers: for instance, *c(1,2,3,4,5)* can be summarized as *c(1:5),* or just *1:5*. In the following, this notation will be used.

A7.4. Importing data from the database

To extract data from the database and import them into the R environment, a function called *fetchTS()* has been created. It takes the following arguments:

- *id.ts*: A number (or a vector of numbers) corresponding to a time series identification number in the database.
- *sync* (optional): If *sync=TRUE,* kernel smoothing will be applied to the time series. This ensures that different time series will share time stamps. Notice that smoothing is also low-pass filtering. This means that fast dynamics are damped.

The user can import one time series at a time,

```
> fetchTS(991)
Time series 991 has been successfully imported
> fetchTS(434)
Time series 434 has been successfully imported
> fetchTS(73)
Time series 73 has been successfully imported
```

Or many time series at a time using the operator *c()* to create a vector of identification numbers:

```
> fetchTS(c(991,434,73,74,78,79,22,25))
  Time series 991 has been successfully imported
  Time series 434 has been successfully imported
  Time series 73 has been successfully imported
  Time series 74 has been successfully imported
  Time series 78 has been successfully imported
  Time series 79 has been successfully imported
  Time series 22 has been successfully imported
  Time series 25 has been successfully imported
```

Remark: the serial order of the identification numbers does not matter, for each time series imported, a confirmation statement informs the user that the operation has succeeded, there is no restriction on the number of time series (= length of the vector) to be imported but the user must be informed that if too many time series (>30) have been imported, it can significantly affect/slow down the performance of the program running..

A list of the time series already imported into the R environment can be obtained by calling the *listTS()* function which does not take any arguments:

```
> listTS()

 Time series already imported into the R environment:
        22   19780-0100-KØC1-EM1_FORBR_IDAG_LOG_X
        25   19780-0100-KØC2-EM1_FORBR_IDAG_LOG_X
        434   19780-0103-VEN3-IRR324-RT01_LOG_X
        73   19780-0100-VEN2-VI1_P_LOG_X
        74   19780-0100-VEN2-VU1_P_LOG_X
        78   19780-0100-VEN3-MK1_LOG_X
        79   19780-0100-VEN3-MK2_LOG_X
        991   1243031_temp
```

Invoking *listTS()* generates a list of time series which can be identified by the combination of the number and the name defined in the database.

It is possible to remove a time series which will not be used any longer in the session by invoking the *removeTS()* function in the same way as the *fetchTS()* function:

```
> removeTS(c(73,434))
> listTS()

 Time series already imported into the R environment:
        22   19780-0100-KØC1-EM1_FORBR_IDAG_LOG_X
        25   19780-0100-KØC2-EM1_FORBR_IDAG_LOG_X
        74   19780-0100-VEN2-VU1_P_LOG_X
        78   19780-0100-VEN3-MK1_LOG_X
        79   19780-0100-VEN3-MK2_LOG_X
        991   1243031_temp
>
>removeTS(-1)
```

```
>listTS()

>
```

Remark: by passing *-1* as an argument, the *removeTS() function* removes any time series previously imported

A7.5. Errors

If there is no time series in the database corresponding to the identification number in the arguments, an error message is returned:

```
> fetchTS(1200)
  Error in typeTS(id.maal, id.tac, id.dong, id.ik.log)
  ERROR: identification number 1200  is not correct
>
```

If there is an error in the syntax of the command line (the user forgets to call the vector operator *c()* when importing many time series at a time for instance), an error message will be generated by the program:

```
> fetchTS(991,434,73,74,78,79,22,25)
  Error in fetchTS(991,434,73,74,78,79,22,25)
  unused argument(s) (434,73,74,78,79,22,25)
>
```

A7.6. Getting information about a time series

Basic statistics are provided by the function, *summaryTS()*. A simple example:

```
> summaryTS(c(80,87,93))

      N.obs  N.hours  s.p. [min]  Mean  Median     sd   <15   <19   >26   >28
80   74922      311           5   2.50    0.00   8.46 0.955 0.965 0.024 0.022
87   74922      311           5  25.31    0.00  39.07 0.645 0.667 0.303 0.292
93  74922       311           5  10.03    8.97   5.91 0.764 0.929 0.009 0.000
```

N.obs is the number of considered observations, *N.days* is the number of days over which the observations are spanning, *s.p.* stands for “sample period” (units are in minutes). *Mean*, *Median* and *sd* (standard deviation) then follow before the fractions of the observations that are less than or greater than different values. The default fractions shown are “less than 15”, “less than 19”, ”greater than 26”, and “greater than 28”. These can be specified with the “lt” (less than) and “gt” (greater than) options.

```
> summaryTS(c(93,80,87),lt=c(21),gt=c(31))

      N.obs  N.days  s.p. [min]  Mean  Median     sd    <21    >31
80  74884      311           5   2.50    0.00   8.46  0.969  0.019
87  74884      311           5  25.33    0.00  39.07  0.678  0.278
93  74884      311           5  10.03    8.97   5.91  0.963  0.000
```

Remark: The output from *summaryTS()* may be too wide to fit the R console and will therefore split into more lines which can be confusing. If needed, the width used by the R console can be changed to for instance 100 characters (default is 80) with the command:

```
> options(width=100)
```

The output can also be written to a "comma-separated values" (csv) file which can be imported to other software. This is done with the *csv* option which must be assigned with a string:

```
> summaryTS(c(93,80,87),lt=c(21),gt=c(31),csv="csvfile.csv")
```

A7.7. Graphics

Generating graphics is a multi-step procedure. The user first initializes graphical settings such as the number of sub-windows and the titles, X axis labels, Y axis labels for each sub-window. Then, the user defines the time series to be plotted, a time interval and whether he wants to save the graphic as a JPEG file.

A7.7.1. Graphical setting initialization

Invoking the *optgraphTS()* function requires several arguments to be passed in the right order:

- nb.wind: The number of sub-windows of the plot.
- title: A title for each sub-window (a character string or a vector of character string).
- x.label: X axis label for each sub-window (a character string or a vector of character string).
- x.label: Y axis label for each sub-window (a character string or a vector of character string).

Below come a few examples (lines starting with # are comments):

```
# 1 window, no title, no label
> opt <- optgraphTS(1,"","","")
# 2 sub-windows, no title, no label
> opt <- optgraphTS (2,"","","")
# 1 window, title & both X and Y labels
> opt <- optgraphTS (1,"April 2008","Time","Temperature")
# 2 sub-windows, same title & labels for both windows
> opt <- optgraphTS (2,"April 2008","Time","Temperature")
# 2 sub-windows, same title & X labels but different Y labels
> opt <- optgraphTS (2,"April 2008","Time",c("Temperature","Humidity"))
```

A7.7.2. Plotting a time series

Generating graphics requires to call the *graphTS()* function and pass the following arguments:

- id.ts: A time series identification number (or a vector of identification numbers), the user has to make sure that the time series corresponding to that/those number(s) has/have already been imported into the R environment (via the *fetchTS()* function).
- nb.wind: The number of sub-windows of the plot (it has to be the same as in the *optgraphTS()* function).
- ts.wind: A vector of integers which represent the windows in which the time series will be plotted. E.g., if plotting three different time series, and the first one should be plotted alone in the first plot, and the other two together in the second, use *ts.wind=c(1,2,2)*.
- interval: A vector of time interval of the form *c(yyyymmdd,yyyymmdd)*
    - *c(0,0)*: Default time interval, plot the time series from 1 July 2007 to 31 October 2008.
    - *c(20080501,20080501)*: plot the time series over 1 May 2008.
    - *c(20080501,20080531)*: plot the time series from 1 to 31 May 2008 (included).
- opt: The name of the object which contains the graphical settings (allocated by calling the *optgraphTS* function).
- saveGraph: Set equal to *TRUE* (save the graph as a jpeg file) or *FALSE* (do not save any graph).
- grid: If set to *TRUE*, a grid will be drawn in the figure.
- legendpos: By default, the position of the legend is calculated from the plot and tried to be put at the right border of the plot. If this fails, the user can in stead use legendpos = "string", where string is one of "*bottomright*", "*bottom*", "*bottomleft*", "*left*", "*topleft*", "*top*", "*topright*", "*right*". The legend will then be put inside the plot but at the border at the position described by the string.
- yaxt: In some cases, the ordinate axis is not well rendered. In such case, try setting this option to "axis".

Some restrictions have been set up:

- The number of windows is limited to 4 (0<nb_wind < 5).
- The number of time series to be plotted per sub-window is limited to 10.

Below come a few examples:

```
> opt_1 <- optgraphTS(1,””,””,””)
> graphTS(434,1,1,c(0,0),opt_1,T)
```

```
> opt_2 <- optgraphTS(1,”Room 324 (TAC Measurements)”,”Year 2008”,”Temperature”)
> graphTS(434,1,1,c(20080424,20080430),opt_2,T)
```

```
> opt_3 <- optgraphTS(1,”Room 324 (TAC vs. IK Measurements)”,”Year
2008”,”Temperature”)
> graphTS(c(991,434),1,c(1,1),c(20080424,20080430),opt_3,T)
```

```
> opt_4 <- optgraphTS(4,c(“Room 324 (TAC vs. IK Measurements)”,””,””,””), “Year
2008”,c(“Temperature”,””,””,””))
```

```
> graphTS(c(991,434,73,74,79,78,25,22),4,c(1,1,2,2,3,3,4,4),c(20080424,20080428),
opt_4,saveGraph=T,legendpos="topleft")
```

```
> opt_5 <- optgraphTS(3,c("VEN3-MV1","VEN3-RV1","VEN3-UT1"),"24-28 April
2008","")
> graphTS(c(80,87,93),3,c(1,2,3),c(20080424,20080428),
opt_5,saveGraph=T,legendpos="topright")
```

The name of the generated graphic file is a combination of the identification number and the time interval. For instance:

Function call	Name of saved file
optgraphTS(434,1,1,c(0,0),opt_1)	fig_434_20070701_20081101.jpeg
optgraphTS(c(434,991),1,c(1,1),c(0,0), opt_1)	fig_434_991_20070701_20081101.jpeg
optgraphTS(c(434,991,22),2,c(1,1,2), c(0,0),opt_1)	fig_434_991_22_20070701_20081101.jpeg
optgraphTS(c(434,991,22),2,c(1,1,2), c(20080424,20080428),opt_1)	fig_434_991_22_20080424_20080428.jpeg

To display graphics files, click on the Home Folder icon on the left hand side of the bin icon and the path: */home/??/MultiParamContr/graphs* ("??" stands for the login name of the user, “pdel” in figure A7.4 for instance).

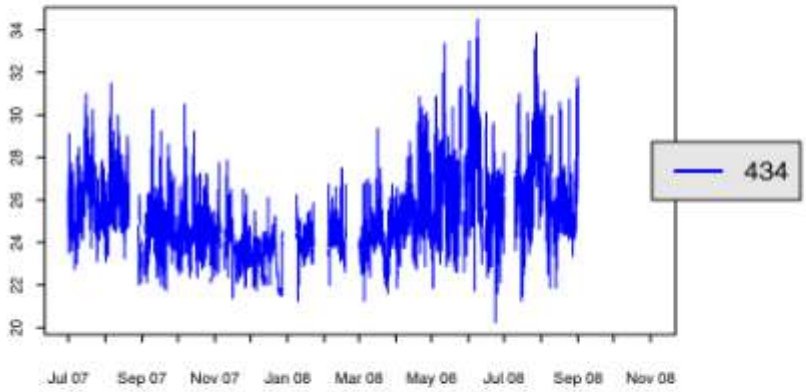


Figure A7.7. Resulting graph from the first example on the use of *graphTS()*.

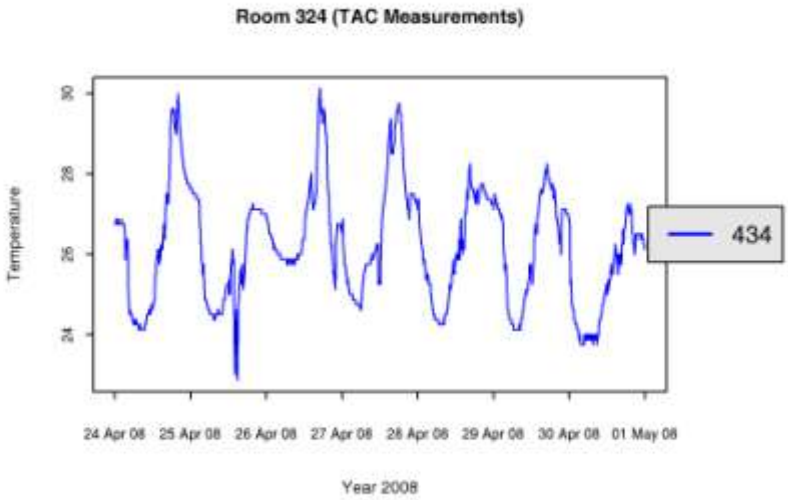


Figure A7.8. Resulting graph from the second example on the use of *graphTS()*.

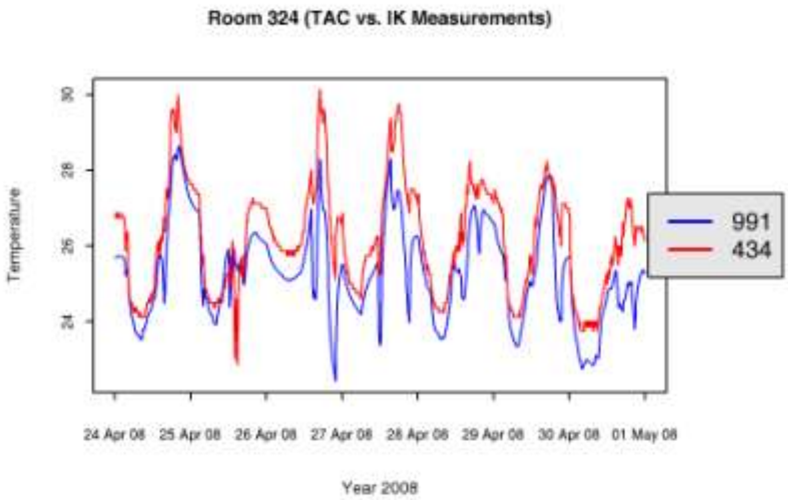


Figure A7.9. Resulting graph from the third example on the use of *graphTS()*.

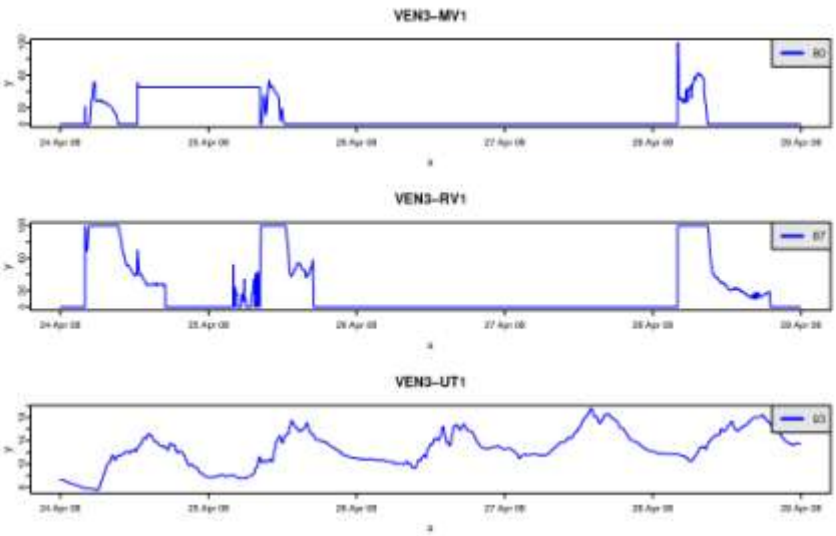


Figure A7.10. Resulting graph from the fourth example on the use of *graphTS()*.

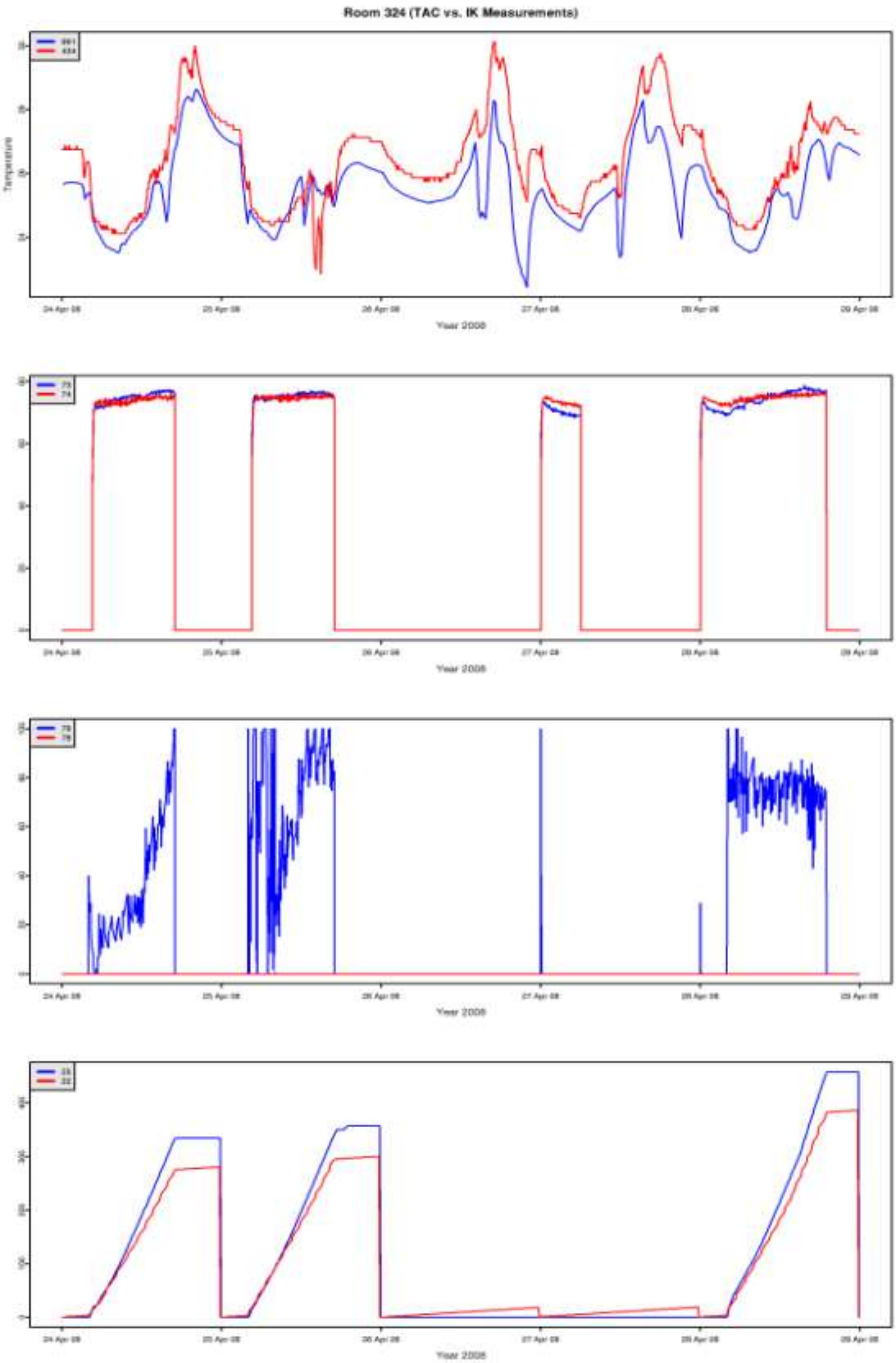


Figure A7.11. Resulting graph from the fith example on the use of *graphTS()*.

A7.8. Estimating distribution functions

You may want to have a more complete view of the distributions of the data in a time series. For this, you can use the *cdfTS()* function. It uses the “opt” argument like *graphTS()*. First the title and axis labels are defined. These graphical parameters must be provided when generating a plot. Here for time series 21:

```
> opt_cdf <- optgraphTS(1,”Estimated CDF for time series 21”, “Consumption”, “P(C<c)”)
> fetchTS(21)
> cdfTS(21,opt=opt_cdf)
```

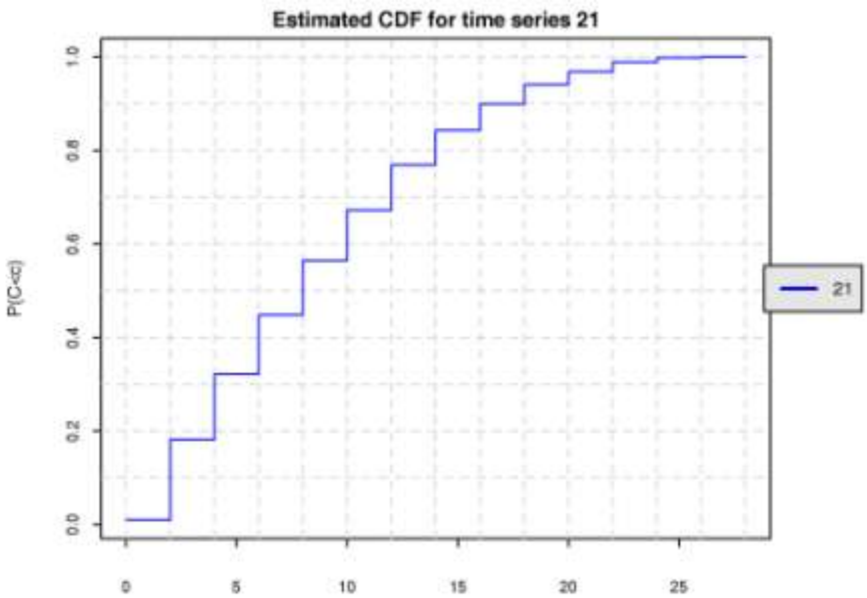


Figure A7.12. The estimated cumulative distribution function for time series 21.

The function takes the following optional arguments:

- savename: If present, the plot will be written to a jpeg file in *~/MultiParamContr/graphs/* with the name given, appended with .jpeg if needed.
- start: The lower value of the range of interest. This can be useful if outliers are present in the lower region.
- end: The upper value of the range of interest. This can be useful if outliers are present in the higher region.
- step: The distance between the values of the explanatory variable for which the cdf is estimated.
- interval: As for the function *graphTS()*, the time interval that must be considered. c(0,0) is default and means the full period.
- nb.sub: Number of windows (like in *graphTS()*). Default is 1.
- ts.wind: A vector describing in which windows the different time series will be plotted. The default is that all are plotted in the first window.

An example with two time series and some more options used:

```
> opt_cdf2 <- optgraphTS(1,”Estimated CDF for time series 21 and 991”,”Consumption”,
“P(C<c)”)
```

```
> cdfTS(id.ts=c(21,991),nb.sub=1,ts.wind=c(1,1),start=10,step=1,end=25,opt=opt_cdf2,
savename="cdf_21_991")
```

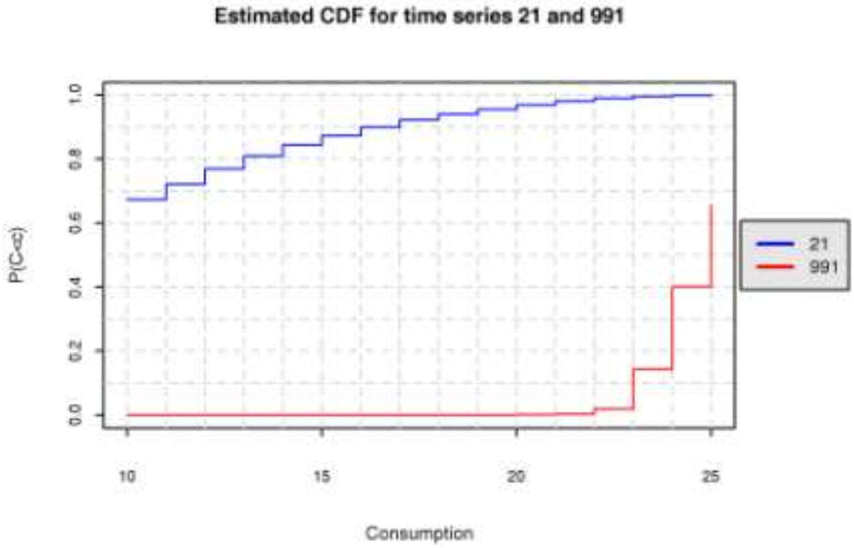


Figure A7.13. Estimate of two different time series. The ranges of the series differ and depend on chosen units. The chosen range in this example does not entirely cover the two ranges of the time series.

A7.9. Filtering a time series with specific days/hours

filterTS() is a function to strip a time series to only include observations from specific time of week and day. Default is Monday to Friday from 8 a.m. to 5 p.m. To obtain this for the time series number 21 and 991, just type:

```
> filterTS(c(21,991))
```

However, two options, days and hours, control the filtering and can be adjusted by the user. Notice that for days, day 1 is Monday, while day 6 is Saturday, and day 0 is Sunday. Regarding hours, the hours given are the hours numbers. For instance *hours=16* corresponds to the time period from 4 p.m. to 5 p.m.

To filter on Tuesdays, from 10 a.m. to 11 a.m:

```
> filterTS(c(21,991),days=c(2),hours=c(10))
```

To filter on Sundays and Mondays, from 3 a.m. to 4 a.m:

```
> filterTS(c(21,991),days=c(0,1),hours=c(3))
```

To filter on Mondays, Tuesdays and Thursdays, from 3 a.m. to 4 a.m:

```
> filterTS(c(21,991),days=c(1,2,4),hours=c(3))
```

To filter from Mondays to Fridays, from 3 a.m. to 4 a.m:

```
> filterTS(c(21,991),days=c(1,2,3,4,5),hours=c(3))
```

or

```
> filterTS(c(21,991),days=c(1:5),hours=c(3))
```

To consider only a certain period, you can use the option, *interval*. The default is returning data over the entire interval covered by the time series. *interval* uses the same syntax as in *graphTS().*

To filter from Mondays to Fridays, from 8 a.m. to 12 a.m and from 2 p.m. to 5 p.m:

```
> filterTS(c(21,991),days=c(1:5),hours=c(8:11,14:16))
```

Notice that *filterTS()* modifies the relevant time series directly. The time series then only consists of the mentioned observations. If further work is going to be carried out on the non filtered time series, the user can invoke the *fetchTS()* to restore them.

A7.10. First order differentiation

The *diffTS()* function performs a first order differentiation of the specified time series. A special case is implemented to convert energy consumption recordings to power consumption estimates. Notice that this means that drops are treated differently, i.e. as recalibration of recordings. In these cases a positive estimate of the power consumption is returned.

The function takes the following optional arguments:

- ts1: The reference number to the time series to difference.
- a: A linear calibration constant (slope) to apply to the differenced series.
- b: A intercept to subtract from the differenced series.}

If a and/or b is passed to the function, the following re-calibration is applied after differentiation (with the standard values, a=1, b=0, it does not have any effect):

rdts = dts . a - b

where the original time series is denoted *ts*, the differenced one *dts* and the returned time series *rdts*. Nothing is returned but the resulting time series is written to the workspace. If the name of the original time series is called ts_X, the differenced one will be called ts_X.X.

```
> fetchTS(434)
> diffTS(434)
> listTS()

  Time series already imported in the R environment:
        434       19780-0103-VEN3-IRR324-RT01_LOG_X
        434.434      Time series differentiated

> opt=optgraphTS(2,c("Time series 434","Differentiated time series 434"),"","Air temperature [C]")
```

```
>graphTS(c(434,434.434),2,c(1,2),c(20070701,20080901),opt=opt,legendpos=”topright”)
```

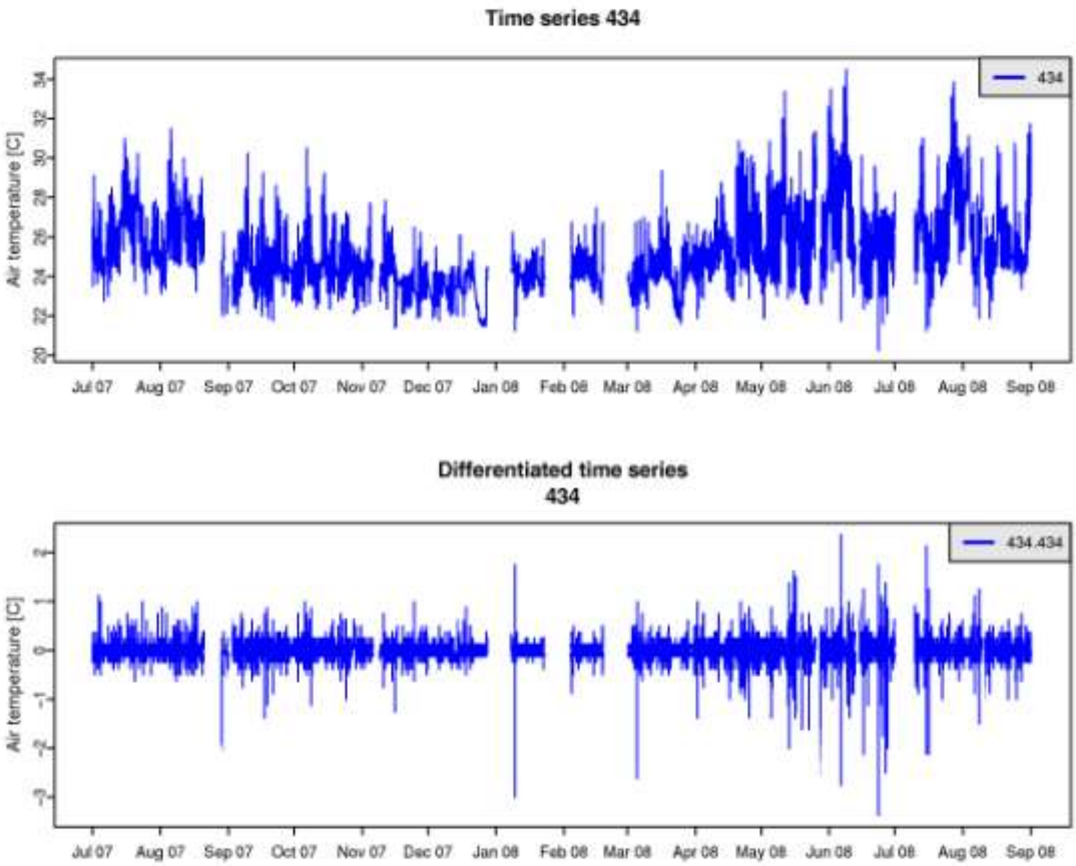


Figure A7.14. Time series vs. Differentiated time series

A7.11. Scatter plots

The *scatterTS()* function provides a graphical display of the relationship between 2 time series or variables. The data are displayed as a collection of points, each having the value of one variable determining the position on the horizontal axis and the value of the other variable determining the position on the vertical axis. The data displayed have been cleaned and smoothed out. Along with the graphical display, a summary on the regression analysis is given. One should consider the value of the R^2 score, *Multiple R-squared* in the R outputs, the closer to 1 the better.

The function takes the following optional arguments:

- id.ts1: A time series identification number (no need to first call the *fetchTS()* function). The corresponding time series will be assigned to the X axis.
- id.ts2: A time series identification number (no need to first call the *fetchTS()* function). The corresponding time series will be assigned to the Y axis.
- opt: The object that contains the graphical settings (allocated by calling the *optGraph()* function).
- x.axis: Limits of the X axis. It can only be used as a graphical setting but not to filter the time series.

- y.axis:Limits of the X axis. It can only be used as a graphical setting but not to filter the time series.
- reg: Set equal to TRUE (plot a linear regression curve) or FALSE.
- intercept: Set equal to TRUE (the linear regression model include an intercept term and therefore the linear regression curve will not cross the point (0,0)) or FALSE.
- saveGraph: Set equal to TRUE (save the graph as a jpeg file) or FALSE (do not save any graph).

```
>.opt1 = optgraphTS(1,””,”Air temperature [C] in room 323”,”Air temperature [C] in room 324”)
> scatterTS(429,434,opt=opt1,reg=T,intercept=F)
Call:
lm(formula = ts_y ~ ts_x - 1)

Residuals:
      Min        1Q    Median        3Q       Max
 -2.99726  -0.22700  0.04782  0.23988  2.41153

Coefficients:
        Estimate    Std. Error  t value        Pr(>|t|)
ts_x  1.013e+00   9.446e-05   10721   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4409 on 35099 degrees of freedom
 (11845 observations deleted due to missingness)
Multiple R-squared: 0.9997,     Adjusted R-squared: 0.9997
F-statistic: 1.149e+08 on 1 and 35099 DF,  p-value: < 2.2e-16
```

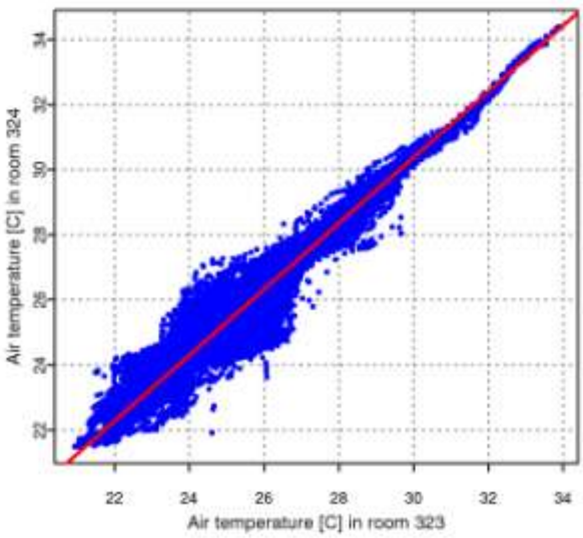


Figure A7.15. Scatter plot of two time series.

A7.12. Saving the session and exiting R

To save your session such that command history, imported data, etc. will automatically be re-read when starting R next time, you have two functions. One is *save.image()* which you can invoke at any time. When quitting R, you can also just use *q()* and answer *y* to saving your session:

```
> q()
Save workspace image? [y/n/c]: y
```

Remember that this has nothing to do with the text file(s) you are editing with *Emacs*. Remember also to save this/these from *Emacs* before disconnecting.

Appendix 8

Strategi og energioptimering af bygningsdriften i bygning 15
Tuborg Boulevard 12