A COMPARATIVE ASSESSMENT OF TWO HVAC PLANT MODELLING PROGRAMS

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ABSTRACT

A comparison is made between two thermal simulation modelling programs with particular reference to HVAC plant modelling. The two programs, APACHE and TRNSYS, were set up using identical building data, plant data and the same meteorological database. A seven-zone constant air volume system with a further four heated and naturally ventilated zones was considered. Hourly time series results of a variety of plant and zone air conditions for a three-day winter period and three-day summer period were compared; each period containing a substantial plant shut down phase. Certain groups of results compared very well indeed - most notably zone air-conditions in winter, whilst comparative zone air and plant air conditions in summer contained some significant inconsistencies.

INTRODUCTION

Thermal simulation programs for analysing energy in buildings have developed rapidly since the 1970's and work, primarily in the UK, to establish the integrity and validity of these programs started in the mid 1980's. In key work, Bowman and Lomas identified three approaches to program validation [(1)]; analytical verification, inter-program comparison and empirical verification. In the first of these, results predicted by a program are compared with solutions that can be accurately obtained by analytical means. In the case of inter-program comparison, results from two or more programs are compared, and with empirical verification, results are compared with field or experimental measurements.

Limited progress has been made on analytical verification (e.g. Bland [(2)], Steffanizzi et al [(3)]). This method is restricted in that there are few occasions where a precise analytical solution can be obtained with the result that the method is limited to a small number of situations involving a single variable with a limited range of inputs.

Inter-program comparisons are restricted in that they reveal the degree of consistency between different programs but this is not necessarily consistent with reality (Wiltshire and Wright [(4)]). Nevertheless, this method does give some early insight into comparative program performance and is useful for identifying possible errors and limitations in program methodologies and algorithms (see for example Lomas et al [(5)]).

Empirical verification represents the most comprehensive and reliable approach to program validation but is restricted due to limited availability of empirical data sets of adequate quality and detail. Nevertheless a considerable amount of work has been reported based on comparisons between program predictions and measurements from simple passive test cells [(6,7,8)] with very mixed and inconclusive results. It is likely, as Lomas suggests [(9)], that with premium resources needed to obtain quality experimental data, future program verification may well need to rely on inter-program comparison based on empirically validated "benchmark" programs.

Most of the program verification work reported so far has been restricted to programs applied to passive or heated and naturally ventilated cases. Nevertheless Chow et al [(10)] have compared BLAST 3, DOE 2 and ESP 7 with experimental results of an air conditioned office space in Hong Kong from the point of view of terminal energy demand and zone conditions. Underwood et al [(11)] reviewed a large number of programs from the point of view of their usability in the analysis of HVAC plant and controls though this work did not consider modelling results from the programs.

In this work, an inter-program comparison of APACHE System Simulation and TRNSYS is made with particular reference to HVAC plant and control system modelling. Of particular interest is the short-term comparative performance of the programs (several days), with a view to their application to control strategy and plant performance analysis rather than longer-term seasonal energy predictions. A model of a constant volume air conditioning system serving seven zones of an eleven-zone floor of a building forms the basis of the comparison. The model includes four heated and naturally ventilated zones. The air conditioning system model includes primary air conditioning plant consisting of mixing dampers and summer pre-cooling, and each air conditioned zone has terminal heating and cooling coils. Results from two air-conditioned zones on opposite orientations of the building are presented.

THE PROGRAMS

Version 14.1 of the TRNSYS program was used [12]. TRNSYS is a fully modular simulation program consisting of a large number of program-standard components. Central to TRNSYS flexibility is the ease with which the user can develop and incorporate bespoke components. As a program whose roots lie in solar energy system simulation, standard components for HVAC plant and control are limited, particularly for UK applications. Therefore, a number of user-written control components were used in the TRNSYS simulations; a modulating control valve incorporating three term controller, and a modulating mixing damper set incorporating a three term controller. These components are based on developments carried out in earlier work (see Underwood [13]).

Version 7.3 of APACHE was used [14]. It has been developed specifically for air conditioning system simulation. The component library is sufficiently comprehensive for UK applications; though the user cannot conveniently add to this should the need arise.

TRNSYS is capable of rigorous plant and control modelling. Many of the components are fully dynamic but it is limited by its use of a response factor building modelling algorithm, a method which is particularly apt for hourly time series modelling, requiring corrections for time intervals of less than one hour - which will mostly occur when control system analysis is of interest. APACHE on the other hand uses a finite difference building modelling algorithm which functions well at a variety of time intervals, though the minimum allowable time interval is one minute. It adopts simple linear steady-state plant modelling and control action is restricted to proportional or on/off.

THE BUILDING

A campus building at the University of Northumbria was chosen as the subject of the modelling; the Northumberland Building. Though not fully air conditioned at present, this building was chosen because it is currently the subject of extensive energy monitoring enabling some empirical verification studies on the two thermal models to be carried out at a later stage. The building, with its major axis east-west, consists of four main floors, which are typical in layout having south facing and north facing rooms separated by a central corridor. Only the top floor was considered in this work.

The building has been recently refurbished to UK Building Regulation standards, including double-glazing and fabric insulation improvements and is used as a mixed teaching and IT laboratory facility. It operates from Monday to Saturday each week, with hours of occupancy 08.00-20.00hrs Monday to Thursday, 08.00-17.00 Friday and Saturday, unoccupied Sunday.

THE TRNSYS MODEL

A sequenced constant air volume system was designed and sized using conventional CIBSE Guide methodologies. Sequencing in this context refers to the mutually exclusive control over room heating and cooling processes. Thus cooling will only commence after the corresponding zone heating coil has shut off. This is alternative practice to reheat control and is commonly used in the UK in situations where there is no need for specific control over room humidity. The primary air plant consists of a mixing damper set with 28% (calculated) minimum fresh air followed by a pre-cooling coil. No pre-heating coil was deemed necessary and no provision was made for winter humidification. Each of the seven air conditioned zones (four north, three south) has terminal heating and cooling coils sized to handle room sensible cooling loads.

Control systems were set to maintain zone air temperature conditions of $20^oC\pm1K$ (winter), $24^oC\pm1K$ (summer). Primary air mixing dampers were set to achieve $12^oC\pm1K$ and the primary air-cooling coil $20^oC\pm1K$ with respect to the primary supply duct condition. Zone terminal heating and cooling coils were controlled from the corresponding return air duct and there was no control over zone humidity.

The basic organisation of the TRNSYS model is given in Figure 1 showing the main data flow paths between the TRNSYS components or "Types". Note that Types T73 (controller-valve) and T74 (controller-damper) are the user written components referred to earlier, all other Types were taken from the TRNSYS library.

THE APACHE MODEL

The APACHE model employed exactly the same data as were used in the TRNSYS case in so far as the user had influence over this. It was possible to ensure that all building and meteorological input data were identical. However certain plant modelling data used in TRNSYS were not needed for APACHE (for example, chilled water and hot water coils required valve characteristic and water flow specifications to be made in TRNSYS whereas these data are not needed in APACHE). Since APACHE could only be set up to provide proportional control, all TRNSYS control loops were set up without integral or derivative action.

In both cases, distributing ducts were not included in the simulation - system components were essentially close coupled. This was done to avoid unnecessary complication.

Figure 2 shows the air system network, which forms the main system file used in APACHE.

SIMULATION CONTROL

Both models were run for January and July using the same Newcastle upon Tyne weather database [15]. Plant switching profiles were set so that the starting day was treated as a Monday. Only three days of results were considered in the comparative analysis - the 27th, 28th and 29th day of each month in which the 28th day is a Sunday and the plant therefore inactive. This combination of days therefore includes a period of plant inactivity as well as a critical period of plant activity (Monday morning). As a result, both models ran for "preconditioning periods" of 26 days - well in excess of the 19-day period suggested by Pinney and Parand in an earlier study [16].

The integration interval used in the TRNSYS model was arrived at after some initial difficulty with numerical stability. A value of 36 seconds was found to give satisfactory stability - it is also the smallest practical value that could be used in TRNSYS. In APACHE the smallest value that could be specified was used - 60 seconds.

A special parameter in APACHE, *the maximum change per time step, f*, allows the user to weight the output of controller modules. This functions by retarding the output of the controller at each time step,

$$p(t+1) = p(t) + \delta(t) \qquad (1)$$

and $$\delta(t) = \frac{f}{P}\left[\theta(t) - \theta(t+1)\right] \qquad (0 \le f \le 1) \quad (2)$$

where $p(t+1), p(t)$ are the control signals at the projected and current time-steps respectively. $\theta(t+1), \theta(t)$ are the controlled variable values at the projected and current time-steps and P is the proportional band setting (i.e. the inverse of the controller gain). The default value for f in APACHE is 0.2. Since the precise value chosen is likely to influence *numerical* stability (as opposed to control loop stability) values for f of 0.2 (the default) and 1 (no influence) were compared.

Run on an Intel 80486, 33MHz - based PC, each TRNSYS run required approximately 5.8 minutes of computer time for 24 hours of simulation time. Correspondingly, APACHE required 42 seconds. Though APACHE uses a finite difference scheme for treating fabric heat transfer, the explicit algorithm used is efficient and plant calculations in APACHE are relatively trivial. TRNSYS however uses an implicit successive-substitution scheme to achieve convergence of the interconnected component variables many of which result from non-linear algebraic and differential equations. This is very computationally demanding particularly when components with low time constants are participating in the simulation, requiring the integration time step to be set with respect to the lowest time constant encountered in the model.

RESULTS

Results are given in the form of air temperatures and associated relative humidities (percentage saturation in the case of APACHE) or moisture contents, at strategic points around the system network - primary air supply, zone air supply and zone. Two zones were selected for the results presented here; a north facing zone and a south-facing zone. The zones were physically similar in all respects, but for orientation.

Results are given in the form of comparative hourly time-series plots for the three-day period (Day 2 is a Sunday during which the plant is inactive).

Zone Temperatures

Excellent winter agreement though TRNSYS exhibits some low frequency oscillation within the specified control proportional band (Figure 3). In summer, plant-active daytime temperatures can be seen to drift within the zero energy band (i.e. between heating and cooling phases) (Figure 5). TRNSYS predicts a substantially higher north zone air temperature than APACHE during the plant-inactive phase as a result of a very rapid rise in zone air temperature after plant shut down. This inconsistency is not evident in other results. Further investigation revealed that the room surface temperatures predicted by TRNSYS were generally higher than those predicted by APACHE. Therefore at night, after plant shut down, the higher stored energy evident in the TRNSYS surface temperatures has increased the zone air temperature by convection to a greater degree than in APACHE. Evident in these results is that the TRNSYS north zone cooling coil is insufficient for the demand. That this pattern is not repeated in south zone results can be explained by the fact that the south zone coil has approximately 30% greater cooling capacity than the north zone coil due to orientation and the period simulated did not reach design solar intensities. Thus the simulated south zone results reflect off-design conditions whilst the north zone results reflect near-design conditions (due to the lack of north zone dependence on direct solar radiation). Evidently then, since the APACHE results for both zones are uncontroversial it is evident that the sizing of the TRNSYS Type56 (cooling coil) is crucial, unlike the much simpler linear APACHE cooling coil model which appears to satisfy design or near design loads when sized using current practice. In particular, there may be a necessity to fix an over-sizing margin to the detailed cooling coil model in TRNSYS for satisfactory load following.

Zone Humidities

Good winter agreements (Figure 4) but, again, poor summer agreements especially in the north zone (Figure 6) which is entirely consistent with the corresponding air temperature results.

Primary and Zone Air Supply Temperatures

In the winter zone supply temperatures (Figure 7), oscillatory action in the TRNSYS results is evident once more (note that plant variables reset to external conditions during plant-inactive periods). APACHE results give smooth agreement with TRNSYS at f=0.2. When the latter is 1, (i.e. no weighting of the controller output), a very poor agreement is evident. The APACHE results at f=1 oscillate with uniform amplitude and frequency so that on some days the results at particular times at equal time intervals might be consistently high, and on another day, consistently low, as can be seen in these results. This is not due to the zone heating coil but to the upstream fresh air damper, which is evident from the similar pattern of behaviour in the primary air temperature result (Figure 9).

In control loops of this type, containing zero thermal capacity when modelled in APACHE, control action must be retarded through f if numerically stable results are to prevail. The effect of this on modelling integrity and accuracy is of course an issue.

Zone air supply results in summer (Figure 8) agree very well in the main. In these results on what is a cool summer period, the fresh air damper is fully open (hence the better agreement in APACHE results with f=1).

Note the glitches in Figure 9 (and elsewhere) which are a characteristic of the APACHE results at plant switching instants. Here, airflow starts or discontinues immediately as a result of plant switching but the corresponding thermal energy balance takes a time step to catch up. The treatment of dynamics within some of the more rigorous TRNSYS plant component models prevents these switching glitches from occurring in TRNSYS.

CONCLUSIONS

This work has attempted to compare the results of two thermal simulation programs with particular reference to the modelling of HVAC plant and control. It was possible to produce identical main input data sets for the two programs, APACHE 7.3 and TRNSYS 14.1, though the latter required additional detailed plant information due to the rigorous nature of its modelling of these aspects.

In the main, results for a three day period including a plant shut down phase compared very well and run times were considerably higher for the TRNSYS program suggesting that the simpler APACHE model offers a practical advantage here. However, the APACHE program introduced uncertainty as to the validity and use of an artificial control loop parameter which acts to retard the change in control signal in a time step. This was found to have a major effect on performance of plant and control loops modelled essentially with zero thermal capacity in APACHE.

There was a serious inconsistency in the prediction of zone air temperature at near-design conditions in TRNSYS due to inadequate capacity at the zone cooling coil, despite sizing according to standard UK practice. This suggests that the sizing method used for the rigorous non-linear cooling coil model of the type used in TRNSYS is critical.

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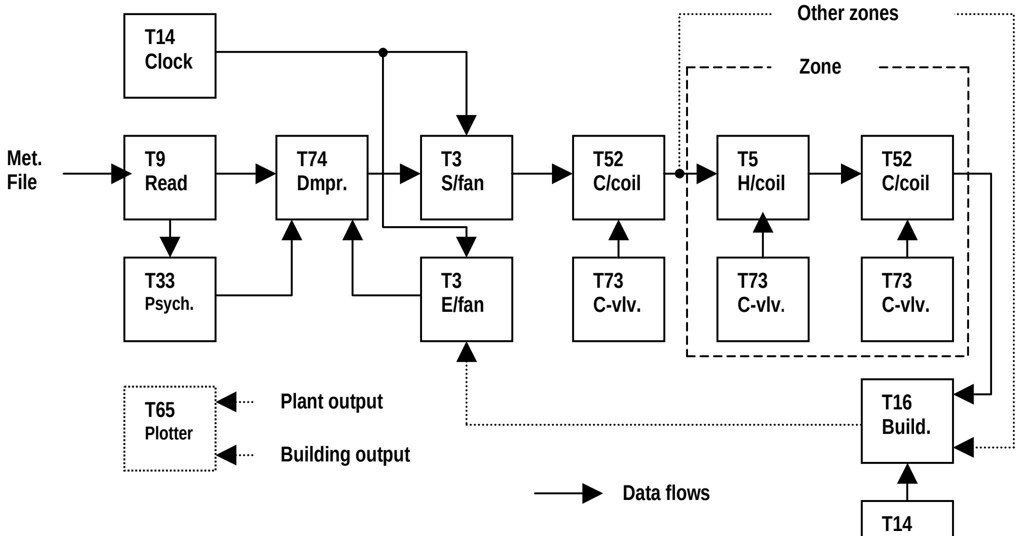

Figure 1: Basic TRNSYS Model Organisation

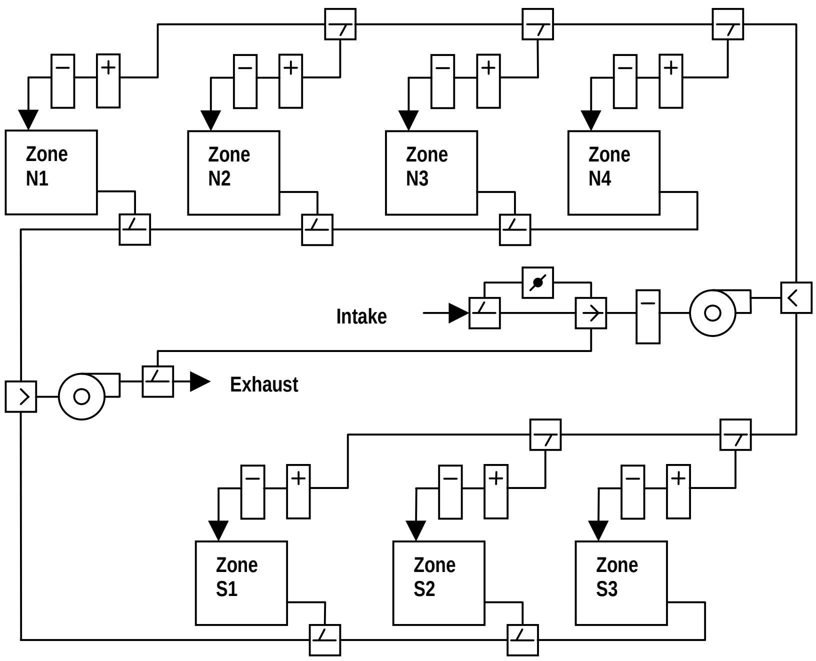

Figure 2: APACHE Air System Connections

KEY TO FIGURES 3-10

Solid line:	TRNSYS results
Circle (scatter):	APACHE (*f*=1) results
Cross (scatter):	APACHE (*f*=0.2) results

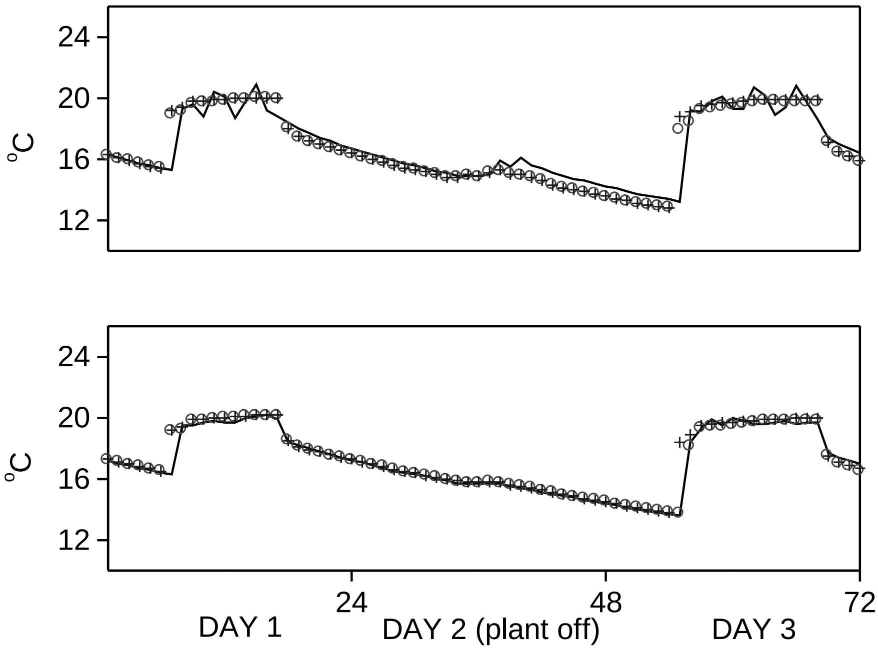

Figure 3: winter zone temperatures (top: south zone, bottom: north zone)

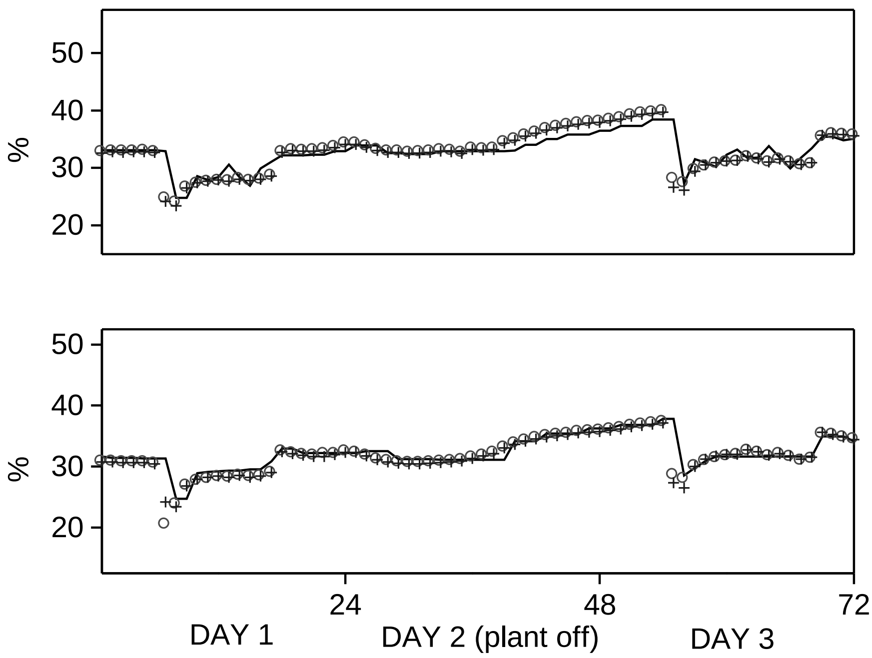

Figure 4: winter zone relative humidities (top: south zone, bottom: north zone)

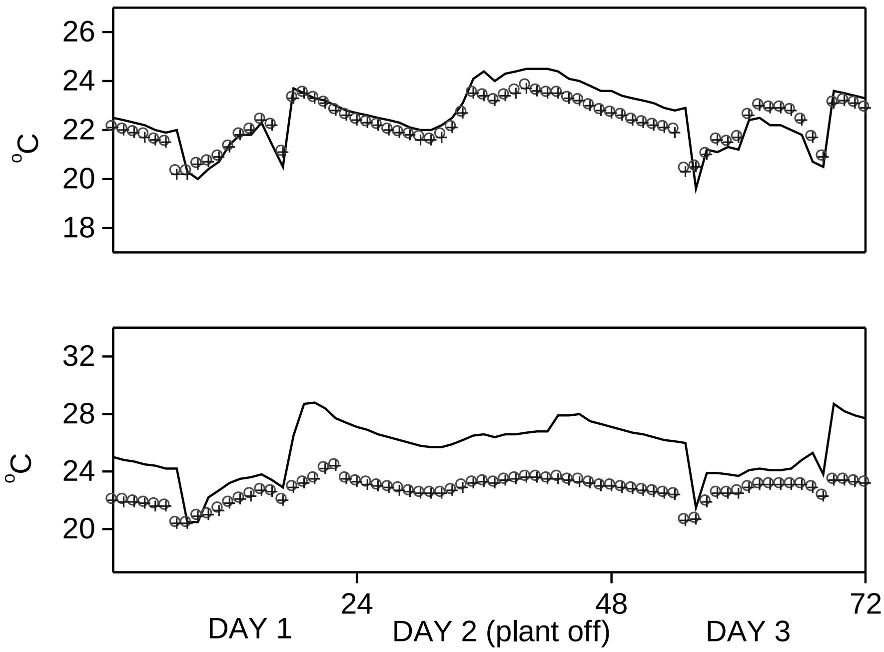

Figure 5: summer zone temperatures (top: south zone, bottom: north zone)

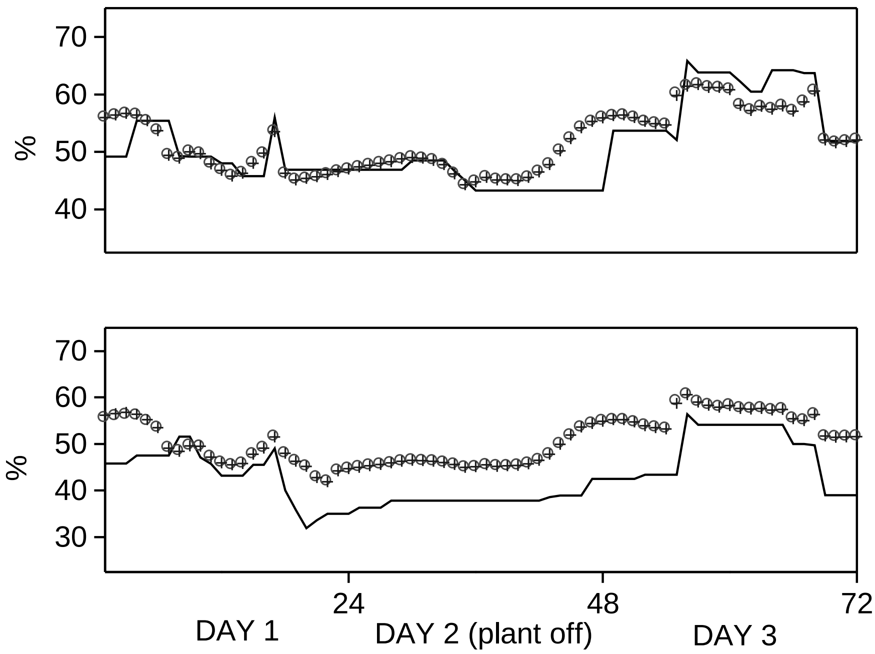

Figure 6: summer zone relative humidities (top: south zone, bottom: north zone)

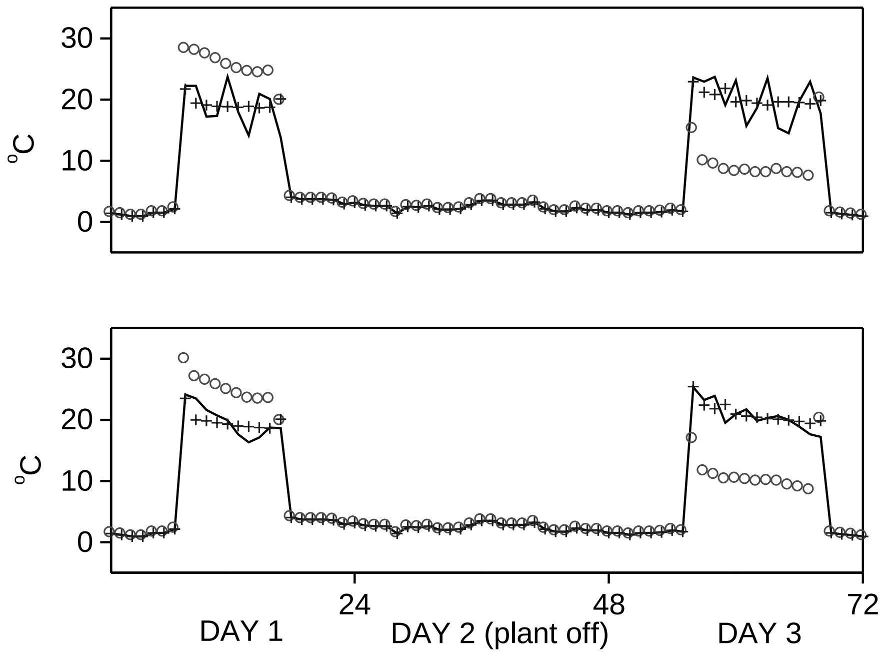

FIGURE 7: winter zone supply temperatures (top: south zone, bottom: north zone)

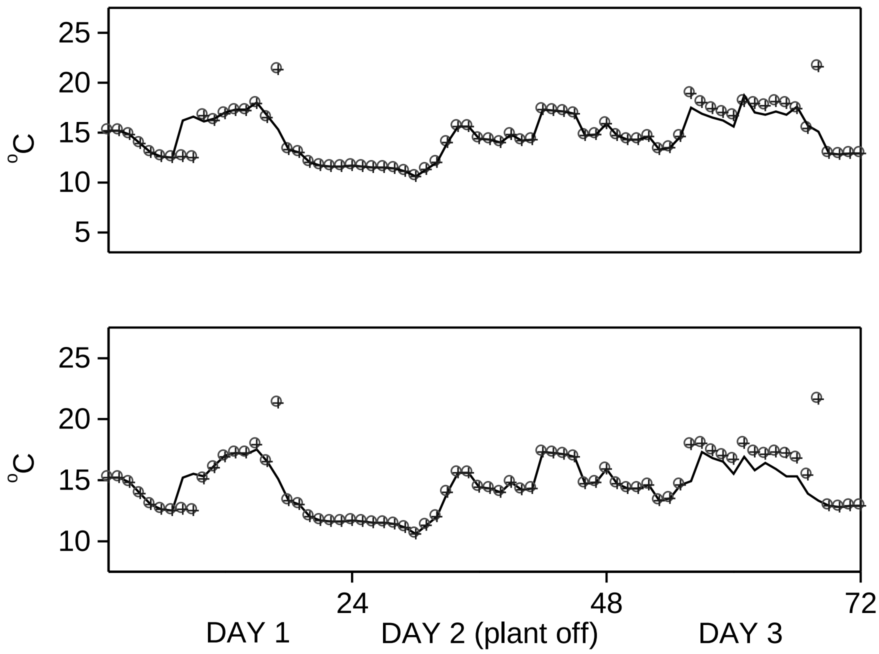

Figure 8: summer zone supply temperatures (top: south zone, bottom: north zone)

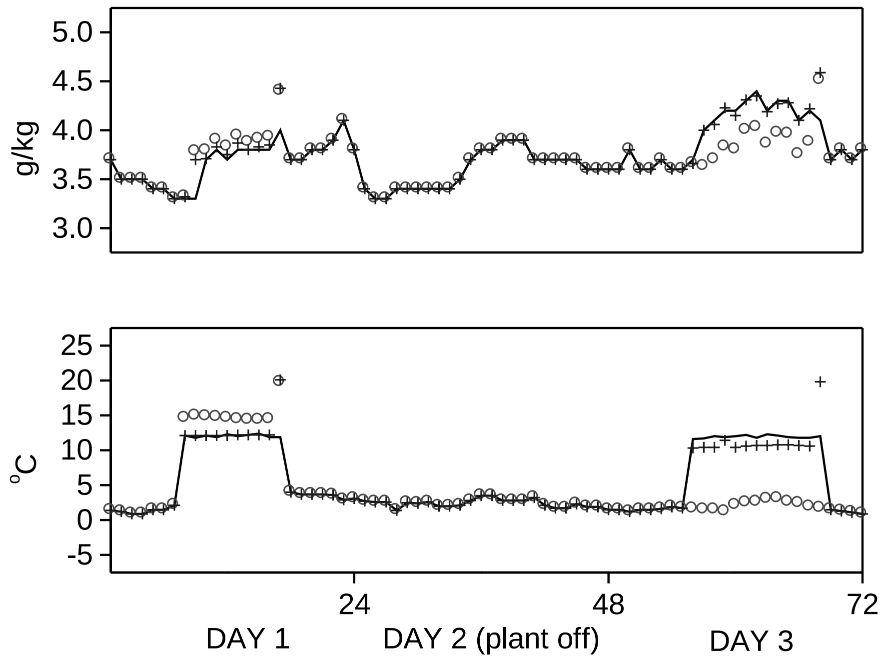

FIGURE 9: winter primary air conditions (top: moisture content, bottom: temperature)

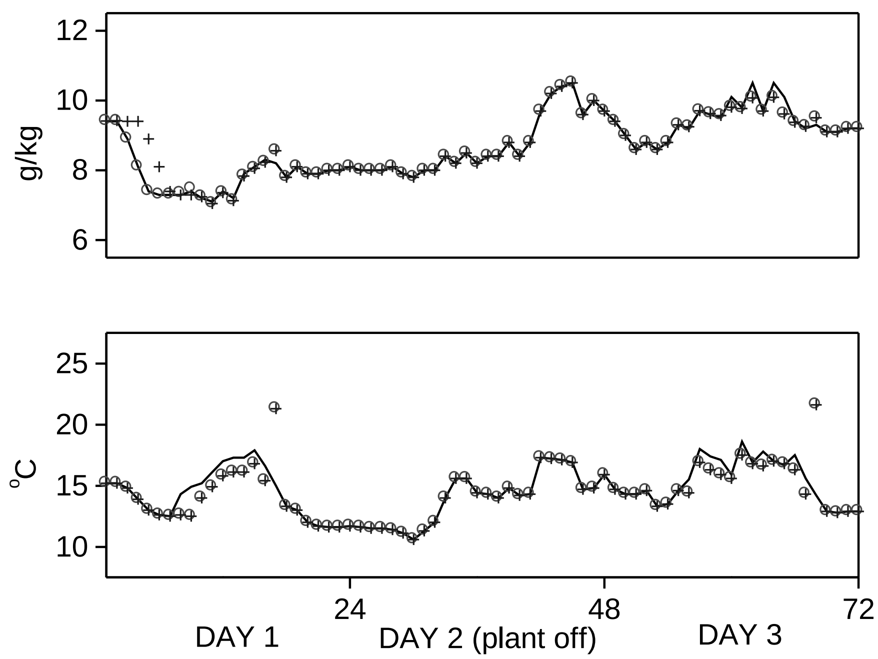

Figure 10: summer primary air conditions (top: moisture content, bottom: temperature)