1. Objectives

The objectives of the research as planned in the original proposal were to perform a pilot study leading to the development of off-line predictive soft-computing based models for three different building types. The rationale behind the research was to see to what extent the soft-computing methodology is suited to each of these building types and to possibly formulate more detailed research proposals in the future focused on particular methods and buildings. The objectives in the original proposal were as follows:

1. to assess the suitability of soft computing techniques for modelling applications in the built sector;
2. to model the temperature and relative humidity of a multivariable HVAC VAV system;
3. to model the air temperature and air quality in a low energy building;
4. to model the internal temperatures for an endothermic system.

All the objectives from the original proposal have been achieved. However, minor amendments were introduced to take into account circumstances not known at the time of the submission of the research proposal. These changes were as follows:

1. to assess the suitability of soft computing techniques for modelling applications in the built sector;
2. to model the temperature and relative humidity in only one of the three air-conditioned rooms in Anglesea Building (all the rooms have similar thermal behaviour);
3. to model the temperature and relative humidity in one of the rooms in the naturally ventilated Portland Building (due to the high price of air quality sensors and the ease with which it is possible to indirectly judge the air quality from relative humidity measurements);
4. to model the temperature and relative humidity in the endothermic St Catherine's Lighthouse (since the Binfield Barn building was not operational during the research period of the project);
5. to perform a component level modelling analysis on one of the test buildings (in order to assess the merits of this approach as compared to the 'systems' level modelling. In this respect the naturally ventilated Portland Building was chosen and the window and the heater were to be viewed as the 'system components').

The above changes in the research activities did not lead to any conflicts or compromises with the main aims of the original proposal, i.e. to carry out a feasibility study on the suitability of soft-computing based models in the built
sector. On the contrary, they focused the project and made it more relevant, and good results have been achieved. Some of the results have already been presented at prestigious international conferences and in recognised scientific journals.

2. Background

There has been a significant interest in the soft-computing methodology and its application in the built sector over the last decade [1]-[6], [8]-[15]. This has been due to two main reasons:

- the increased complexity of building management tasks to be solved, and
- the increased requirements demanded by the users and operators, both in terms of comfort and energy efficiency.

Modern buildings have to incorporate a variety of different and difficult functions such as good climate control, high security guarantees, effective lighting maintenance, fire prevention systems, etc. These are not always easy because of the significant unpredictable stochastic effects due to climatic and occupancy effects. Also, the functions are becoming more 'intelligent' to allow the building management system to be able to respond quickly and efficiently to changes and disturbances. In this way, optimised performance is achieved in an automatic manner. Here, the term "intelligent" is relevant because the soft-computing methodology is known to offer the most promising way of achieving robust and reliable solutions in this respect.

The soft-computing methodology incorporates several techniques the most important of which are fuzzy logic, neural networks, and genetic algorithms [7]. Fuzzy logic is capable of approximate modelling and logical inference, neural networks are characterised by adaptation and learning and genetic algorithms incorporate parallel searching and optimisation features [16]-[20]. These features are believed to be able to increase the intelligence in modern buildings which is a major challenge at present. In this respect, a certain number of investigations have been carried out, but the majority focus on the application of a specific soft-computing technique in a given building rather than considering them in combination which is the underlying idea of the soft-computing approach. Therefore, the purpose of this research project is timely, namely, to carry out a systematic pilot study on the application of soft-computing based modelling to buildings. This work was to apply a combination of different techniques to model several real buildings during the various seasons. Models obtained in this way are believed to be vital in allowing good proactive decisions to be made in operating buildings in a cost-effective and reliable manner to realise truly intelligent buildings of the future.

3. Experimental Facilities

The experimental facilities used in this research project consist of three separate zones in each of the three buildings under investigations. The facilities are fully equipped with approach sensors and communication devices providing automatic computer-logging of a number of internal and external air variables. The air-conditioned zone considered in Anglesea Building consists of three communicating rooms. Each room has a window, which is kept locked to preserve the full effects of air-conditioning. The zone investigated in the naturally ventilated Portland Building also consists of three neighbouring rooms, which do not have interconnecting doors but just one door each to a common corridor. There are heaters in each room that can be adjusted by the occupants and windows that can be opened or closed. The zone considered in the St Catherine’s Lighthouse (endothermic system) includes in fact the whole building consisting of four levels.
situated in a common space, and connected to each other through a spiral staircase, with windows on each level and monitoring was carried out on two sides of the building. In addition, the ambient energy collector is a stand-alone structure situated outside the main Lighthouse building; this was also monitored for modelling purposes. All the test facilities were monitored during the project, and the data from them was used for the research carried out.

4. Programme and Management
The full research programme was completed on time and within the overall budget allocated. Minor changes were introduced to the programme in the original proposal as described in section 1; these extended the aims somewhat and so enhance the results that are presented here. In other words, the research programme was successfully carried out and soft-computing methods for modelling the indoor climate in buildings have been shown to offer good potential. The setting up, instrumentation and maintenance of the research facilities was partially funded and carried out by the industrial partners for the project whose active participation in the management of the research activities was very valuable to the academic investigators. The project was managed through having three-monthly meetings, which were held in rotation at the industrial partners sites. The partners included Caradon Trend Control Systems Ltd, Satchwell Control Systems Ltd, Hampshire County Council, Building Research Establishment, Ambient Energy Systems Ltd and Trinity Lighthouse Service.

5. Main Research Findings
All the project's objectives have been achieved. Soft computing modelling methods have been shown to offer considerable potential for the built sector. Furthermore, the additional objective to investigate component level modelling for one of the test buildings has also been achieved.

The main results from the research are as follows:

- Soft computing modelling methods are well suited for the built sector. However, the methods developed offer the best potential for naturally ventilated buildings.
- Two types of Takagi-Sugeno models, namely fuzzy regression delay (RD) and fuzzy proportional difference (PD) have been developed.
- The RD and PD models can be improved using neural networks and genetic algorithms.
- The models are able to predict temperature and relative humidity to a high level of accuracy and compare favourably with models obtained using traditional methods.
- The results warrant more detailed studies to develop heuristic models based on soft computing methods for the built sector and how they can be incorporated in improving operational performances while optimising resources.

The results arising from the research have been well received by the industrial partners and the built environment research community, when they have been presented at conferences and scientific journals. The main research findings are described in more detail next.

5.1 Fuzzy modelling
The predictive modelling of internal air temperatures and relative humidities was carried out by a Takagi-Sugeno fuzzy model, which has received considerable attention recently because of its suitability for processing information from input-output measurements. This is also the case in building management systems.
where the main information source is the numerical data from sensors rather than expert knowledge, which is difficult to obtain because of the multivariable and stochastic nature of the system to be considered. Another advantage of the Takagi-Sugeno fuzzy model is its capability to approximate non-linear input-output mappings by a number of linearised models at several operating points, and the indoor climate in buildings is known to be characterised by such non-linearities.

The Takagi-Sugeno fuzzy model consists of linguistic if-then rules in the antecedent part and linear algebraic equations in the consequent part. There are two types of parameters in this model: non-linear (in the membership functions in the antecedent part) and linear (in the algebraic equations in the consequent part). The task of the fuzzy model is to determine the initial values of both types of parameters on the basis of the input-output data. This determination is carried out by subtractive clustering, i.e. by assuming that each data point is a potential cluster centre and using all the data to gradually find a reduced set of clusters.

Two types of dynamic fuzzy models are introduced and investigated in the project, namely regression-delay and proportional-difference. The outputs of the regression-delay models depend on regression and delay terms of their inputs while the outputs of the proportional-difference models depend on proportional and difference terms of the inputs. Both types of models reflect different aspects of the dynamics of the indoor climate and the purpose of their explicit consideration in the project is to see to what extent each of these aspects is represented for each of the three buildings under investigation during the cooling and heating seasons. The best short and long-term modelling accuracies obtained with these two models (after the models have been refined using neural networks or genetic algorithms) is presented next. The accuracies are expressed in terms of the root-mean square error of the predicted values when compared with actual measured data.

5.2 Model adaptation by neural networks
The task of neural adaptation is to adjust the fuzzy model parameters in order to obtain a better fit to the real data. The method used in the project is based on back-propagation, i.e. by iterative propagating of the modelling error (the difference between the real and the modelled output) from the consequent to the antecedent part of the fuzzy rules until a specified number of iterations is achieved. Each iteration in the neural adaptation algorithm consists of two stages, namely, the forward and backward stages. In the forward stage, the non-linear parameters in the membership functions are kept fixed while the linear parameters in the algebraic equations are changed. In the backward stage, the opposite procedure is applied.

5.3 Model optimisation by genetic algorithms
The purpose of genetic optimisation is also to adjust the fuzzy model in order to obtain a better fit to the measured data. The method used in the project is based on the idea of real-valued coding, i.e., by representing the individuals with real valued genes and sequentially evaluating the modelled error until a pre-specified number of generations is reached. Each generation in the genetic optimisation algorithm involves two basic operators, namely, crossover and mutation. During crossover, some genes from a pair of individuals are swapped while mutation is based on a random change in a gene of an individual. Both operators are applied to both the antecedent parameters and the consequent parameters.

5.4 Best modelling results
The modelling results are presented in Table 1 for each of the three buildings (Anglesea, Portland and the Lighthouse) over both seasons (cooling and heating), using two prediction intervals (short and long), and for the two most important internal air variables (temperature and relative humidity). The results correspond to a fuzzy model that is either of a regression-delay or proportional-difference type that has been improved either by neural networks or by genetic algorithms. More details about these results are given in the Appendix.
The short-term prediction interval for each building corresponds to a 1-step ahead prediction while the long-term interval corresponds to 24-steps ahead prediction. In this case, one step is equal to the data sampling interval from the sensors. The prediction intervals are meant to reflect the dynamics for each building and for this reason they are not the same. In other words, the length of these intervals is a scaled representation of their dynamics and the modelling accuracy associated with it can be reliably used to analyse the soft-computing modelling methods in a comparative fashion.

Table 1. Results of the modelling RMSE for 1 step-ahead prediction RMSE for 24 step-ahead prediction

<table>
<thead>
<tr>
<th>Building/Season/Sampling Interval</th>
<th>RMSE for 1 step-ahead prediction</th>
<th>RMSE for 24 step-ahead prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anglesea Building (cooling)/ 5 min</td>
<td>0.0875</td>
<td>3.5091</td>
</tr>
<tr>
<td>Anglesea Building (heating)/ 5 min</td>
<td>0.0668</td>
<td>0.3162</td>
</tr>
<tr>
<td>Portland Building (cooling)/ 30 min</td>
<td>0.0600</td>
<td>0.3675</td>
</tr>
<tr>
<td>Portland Building (heating)/ 30 min</td>
<td>0.2307</td>
<td>0.4205</td>
</tr>
<tr>
<td>St Catherine's Lighthouse (cooling)/ 15min</td>
<td>0.1840</td>
<td>1.4744</td>
</tr>
<tr>
<td>St Catherine's Lighthouse (heating)/ 15min</td>
<td>0.0513</td>
<td>0.4133</td>
</tr>
</tbody>
</table>

The prediction accuracy obtained by the soft-computing modelling methods is good in both short and long-term aspects. Results presented in the Appendix also show that the accuracy is in most cases higher than the one obtained by traditional methods that use time-series regression models. A more detailed look at the results shows that the accuracy for temperature prediction is significantly higher than that for relative humidity, and this applies to all types of buildings, seasons and prediction intervals. Hence the methods offer considerable potential for use in the built sector. Overall the models developed for the Portland Building (the naturally ventilated building) give the best results.

5.5 Component level modelling

In addition to the "system-level" based modelling described in Sections 5.1-5.4, a "component-level" modelling study was also carried out in Portland Building during the heating season to see the impact of each component on the prediction accuracy of the soft computing methods. The results from the test are presented below (Table 2) for all the status permutations of the two components considered (window and heater). More details about these results are again presented in the Appendix.

Table 2. Results of the component level modelling (15 min sampling interval) RMSE for 1 step-ahead prediction (15 min) RMSE for 24 step-ahead prediction(6 hrs)

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>RH (%rh)</th>
<th>T (°C)</th>
<th>RH (%rh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0875</td>
<td>3.5091</td>
<td>0.3739</td>
<td>5.2415</td>
</tr>
<tr>
<td>0.0668</td>
<td>0.3162</td>
<td>0.8718</td>
<td>0.3633</td>
</tr>
<tr>
<td>0.0600</td>
<td>0.3675</td>
<td>0.1678</td>
<td>0.4956</td>
</tr>
<tr>
<td>0.2307</td>
<td>0.4205</td>
<td>0.2195</td>
<td>0.3818</td>
</tr>
<tr>
<td>0.1840</td>
<td>1.4744</td>
<td>0.2083</td>
<td>3.1277</td>
</tr>
<tr>
<td>0.0513</td>
<td>0.4133</td>
<td>0.1168</td>
<td>2.7487</td>
</tr>
</tbody>
</table>
The best results were obtained for the case when both components were passive, but in general the component based modelling results are not as precise as those obtained via the system-level based approach.

5.6 Comparison with traditional methods
The models derived using the soft-computing (fuzzy-neuro and fuzzy-genetic) methods developed during the research project were further compared with traditional auto regressive moving average and exogenous inputs (ARMAX) models in terms of short and long-term prediction accuracy for both the system-level and the component-level models. In order to make this comparison more reliable and representative, the same data sets were used. As already mentioned, it has been shown in the Appendix that the soft-computing methods outperform the traditional ones in both cases, but they could be viewed as more complex from a computational point of view.

6. Principal Conclusions
The principal conclusions from the research are the following:

· Soft computing methods offer good potential for modelling the temperature and relative humidity in a variety of buildings;
· The methods developed, overall, offer the best potential for naturally ventilated buildings;
· The models perform better for temperature than for relative humidity for both short and long term predictions;
· Initial fuzzy models can be substantially improved by neural networks and genetic algorithms;
· Neural networks are superior to genetic algorithms in terms of computing requirements;
· Genetic algorithms are superior to neural networks in terms of reliability due to better convergence and their parallel searching nature;
· The performance of the models can be further improved by increasing the number of neural iterations and genetic generations;
· The component level modelling results are generally worse than the system-level ones, but this could be due to the shorter training data sets used;
· Traditional models are worse than the soft computing ones in terms of prediction accuracy, but require less computing power.

These conclusions incorporate the major activities carried out within the research programme including fuzzy modelling, neural network based model adaptation, genetic algorithms based model optimisation, component level modelling and comparisons to traditional modelling methods. All these aspects are discussed in more detail in the Appendix to this report.
From the results presented, it is clear that soft-computing modelling methods give good predictions in terms of both short and long-term horizons. The potential for using the methods in buildings is therefore considerable. The investigators intend to further develop and refine the methods for the purpose of
proactive control so that the next generation of intelligent buildings can be realised. In this respect, a new research proposal is under preparation at present that will be focused on the optimised operation of the naturally ventilated Portland Building.

7. Acknowledgements
The investigators would like to express their gratitude to EPSRC for funding this work, to the full-time Research Associate, Dr A Gegov, for his contribution to the research activities, and to the industrial partners Caradon Trend Control Systems Ltd, Satchwell Control Systems Ltd, the Building Research Establishment, Hampshire County Council, Ambient Energy Systems Ltd, and the Trinity House Lighthouse Service.