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Artificial intelligence and networking in integrated building management systems

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Abstract

In recent years the emphasis has moved towards integrating all a building's systems via centralised building management systems (BMS). To provide a more intelligent approach to the facility management, safety and energy control in building management systems (IBMS), this paper proposes a methodology for integrating the data within a BMS via a single multi-media networking technology and providing the BMS with artificial intelligence (AI) through the use of knowledge-based systems (KBS) technology. By means of artificial intelligence, the system is capable of assessing, diagnosing and suggesting the best solution. This paper outlines how AI techniques can enhance the control of HVAC systems for occupant comfort and efficient running costs based on occupancy prediction. Also load control and load balancing are investigated. Instead of just using pre-programmed load priorities, this work has investigated the use of a dynamic system of priorities which are based on many factors such as area usage, occupancy, time of day and real time environmental conditions. This control strategy which is based on a set of rules running on the central control system, makes use of information gathered from outstations throughout the building and communicated via the building's data-bus. © 1997 Elsevier Science B.V.

Keywords: Knowledge-based; Building automation; Building management; Energy control

1. Background to this work

In November 1990, Brunel University was successful in being awarded a DTI/SERC Link project in association with the insurance corporation Lloyd's of London, Dunwoody and Partners consulting Engineers and Thorn Security Ltd. The project's main aim was to investigate the use of rule-based KBS for integrating building services in high technology buildings. Brunel was the science partner and employed three research assistants to work on the project, one of whom was the author. Thorn Security was the manufacturing partner having recently bought up JEL, which made them a serious company in the field of building energy management systems. Lloyd's had experienced problems with the building control systems in their prestigious new high technology building constructed in 1986 (The Lloyd's 1986 building, referred to in future simply as the Lloyd's building). Lloyd's was thus a source of valuable information along with being an ideal test bed in which to try out some of the ideas proposed during the project. The author's involvement enabled him to gain

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valuable experience of some of the problems involved in high-technology buildings from the point of view of a building's owner, the building's occupants, the consulting engineers who specify building services, control room operators and a building control system manufacturer. It also provided the author with access to a great deal of information from the control systems in the Lloyd's building, some of which has been used in this research work.

2. Integrated building management systems

2.1. Information requirements

As the move towards high-tech buildings increases, the facilities manager's job is also encompassing managing the building's information technology systems. In addition, the facilities manager must understand the organisation's business and be able to assess the effect of failing to provide the required environment. They must also understand the technology employed to control the building and be able to interpret and act on the information it provides. It is pointed out by representatives of the profession that the job is increasingly becoming more complicated owing to these multi-disciplinary requirements [1]. It may be that not many facilities managers wholly fit these demanding criteria and in the future organisations using high-tech buildings will have to look hard to find the appropriate personnel. A rule-based control and management system can be used to bridge this skill shortage by integrating more intelligence into the IBMS itself.

There is currently a great deal of interest in artificial intelligence (AI) technology and in many areas it is now moving out of the research laboratories into practical applications. Knowledge-based systems (KBS) are one form of AI where knowledge is captured from experts and stored as a knowledge-base. A KBS accesses the knowledge-base to diagnose the problem and suggest the best course of action in each case. An intelligent building control system, with a KBS reacting to information fed from the various control sensors in the building, is now a possibility.

To be practical, a rule-based building control and management system must be designed in such a way that the knowledge, coded as rules, is independent of any specific building. It must also be adaptive to changes in the configuration of the building or its services. The rules must operate on the data and information types within a general building description which are consistent irrespective of any one building description. This can be achieved with an object-oriented knowledge-based structure, where rules operate on objects within clearly defined classes. The values of the properties belonging to these objects are specific to the building and its control systems, but independent of the knowledge coded in the form of rules. This data base forms what is known in network management terms as a management information base (MIB). A MIB can be remotely managed over a network running an international standard protocol stack such as SNMP (Simple Network Management Protocol) over a standard transport protocol such as the internet standard IP (Internet Protocol). This network would have to be able to integrate data from all the building's systems.

2.2. Current BMS design

The early designs of integrated building management systems merely collected the outputs from the local controllers dedicated to fire protection, security, HVAC and energy management for central monitoring of all these services. Basically, these inputs to the central computer were exceptional inputs, i.e. showing deviations from the norm which required the operator's attention. Thus integration was an overlay on the existing systems, requiring substantial additional wiring and offering improved management response and automatic logging of system actions. In the case of a computer or communications failure the essential local control functions were still operative.

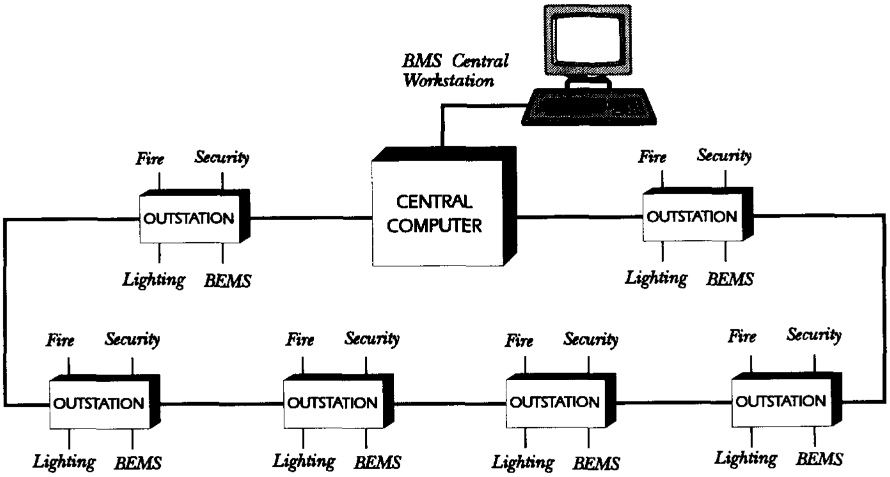

Fig. 1. Integration with distributed intelligence.

A more advanced approach is to integrate the systems using distributed intelligence. This is emerging through the use of microprocessors in local controllers, enabling many more inputs to be monitored and more functions to be performed for less cost. Such controllers are known as outstations and are connected to the central IBMS computer as shown in Fig. 1. This architecture provides the central control computer with the information required for more advanced global control and monitoring functions. The centralised services carry out a series of major global control functions such as boiler start/stop cycles, load shedding, monitor all events, notify the operator of any abnormal conditions and provide advice. It can also support the building's management activity by providing a preventative maintenance schedule.

2.3. The building data-bus

The need for a move towards the integration of building systems is based on the fact that it is common for consultants to specify building-services equipment from many different suppliers. Therefore, there exists a communications problem between all the different systems. One reason for this is that it is very uncommon for any one supplier to produce the best fire, security and energy management systems all within the same product range. Another reason may be that building owners lack confidence in any one supplier to continue to offer the same level of performance on a long-term basis. A good example of this is Lloyd's BMS which includes many high-tech features but is lacking in integration. The systems in this building are supplied by many suppliers using different types of computer hardware, each running different operating systems [1], with no provision for local-area networking or a general sharing of data. As a result, each system provides autonomous control with little integration with any other system, except in the event of fire when the fire alarm system turns the HVAC (heating, ventilation and air conditioning) and transportation systems into emergency mode. This lack of integration is particularly noticeable in the BMS control room where the operators sit in front of an array of control terminals each having different passwords, menus and graphics.

Some companies have tried to overcome this central communications problem through the use of gateways [2]. Gateways aim to achieve integration at the supervisory-computer level of the systems by attempting to make

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[1] The main BMS is run on a Texas Instrument computer; the lighting-control system uses a Digital Equipment PDP11; the lifts and transport controller uses a dedicated processor-board based around the Intel family of computers; the maintenance management system is run on a 80386 based personal computer, running a multitasking operating system. None of these systems communicates with any other.

one computer manage and display the data collected from several systems. The Windows 3 PC-operating-system environment from Microsoft is particularly suited to this task, allowing many gateways to be run simultaneously on one computer and to be displayed on one monitor. Gateways are effectively software interfaces providing protocol translation at a fairly high level, but even with them it has not proved easy to "mix and match" systems designed by different manufacturers. Gateways must be seen as a compromise solution: the most efficient solution would be for all the building systems to operate on a single local-area-network (LAN), communicating via a defined standard protocol.

A common building data-bus would bring down the cost of controlling building services and make complex building management systems more widely available. The current proposal for a building data-bus is that it should be essentially separate from other data networks in the building. In the future it could include other data networks such as computer and telephone communication links. In data technology terms, twisted pair technology is old fashioned and would probably be inadequate for the bandwidth requirements of future desktop applications such as video conferencing which could be many tens of millions of bits per second. Hence at least two data systems are being installed in modern buildings, one based on twisted pair technology and the other on broad-band communications networks such as fibre optic cables. Here we propose the application of a single broad-band networking standard for building management systems namely ATM (Asynchronous Transfer Mode) and describe a methodology for integrating the control functions utilising the data made available by an ATM network using a rule-based approach to the control system.

2.4. *ATM network for building data bus*

ATM is a broad-band version of ISDN (integrated services digital network) and is an emerging standard for local area networking [3]. ATM was first proposed in the late 1960s but was not adopted as a strategy for broad-band integrated services digital network (B-ISDN) until 1986. Since then development was started by the CCITT standards body in 1988 but now standards are being driven by the international ATM Forum. The ATM Forum was formed in 1992 and now consists of more than 500 members from PTT companies, network vendors and research bodies. The ATM Forum is not a standards body but works with ITU, ISO and IEEE.

ATM is a connection-oriented networking standard unlike most current networking standards which rely in the shared broadcast medium concept. In a broadcast system, each end station is physically connected to a common carrier and data is broadcast to each end station irrespective of whether the data is for that end station as in carrier sense/collision detection technologies such as Ethernet or token passing systems such as the Token-Ring networking standard. The connection-oriented principles of ATM networking emerged in the telecommunications fields but they are rapidly being adopted in the local area and metropolitan area workplace. ATM offers the ability to mix different "classes" of data. In this context, classes are defined as data requiring different transport services qualities. For example, a video stream requires very high bandwidth and low latency but not necessarily 100% data reliability whereas typical computer file transfers have a variable bandwidth requirement and require 100% data reliability. Low latency applications are not possible in large bus topology networks such as Ethernet or Token-Ring owing to the nature of bandwidth sharing algorithms deployed. There is no way to prevent a large file transfer from interrupting a video stream or any means of prioritising different data services. ATM is also network technology which can be scaled to match the required bandwidth unlike traditional networking standards. The bandwidth can be scaled to the requirements in different parts of the network. Conventional networking standards just use a constant bandwidth such as 10 MB s^{-1}. ATM offers the possibility for services to reserve bandwidth in the network for their requirements and the ability to span the local and wide area. These properties make ATM very suitable for building management systems where different classes of data within a building can be integrated into one building networking system thus reducing the wiring and different networking technology within the building. Video, data and voice traffic from security systems can be integrated with low latency data such as sensor information and HVAC control signals.

2.5. Integrated control applications

If physical integration, supported by standard protocols or by protocol conversion as appropriate, exists between systems a truly integrated approach to building management can be applied. The introduction of the building data-bus may not, in itself, increase the sophistication and accuracy of control achieved in buildings, but should make control systems cheaper and easier to install and operate. This could provide advantages in the control and operation of all of a building's services. Lighting levels could be accurately controlled and environmental conditions precisely adjusted to meet the requirements of the occupants of the building. Such an IBMS would be able to react quickly to changing conditions, make optimum use of energy, and control maximum demand for electricity. For example, given a requirement to reduce electrical usage under either a peak-demand or time-of-day billing regime, the potential overlay of an electric load-control scheme on an IBMS could accomplish the required load reduction without any significant disruption to services or discomfort to the occupants. In this way, a fraction of the lighting load could be reduced by selective reduction of lighting levels at the perimeter through using either dimming or split wattage fixtures, assuming sufficient daylight is available. Lift speeds could be reduced, or a few lifts temporarily parked. The HVAC load could be temporarily diminished by altering control-loop set points incrementally rather than through a wholesale shutdown of equipment, while generators or uninterruptible power supply (UPS) equipment could be brought into service. Occupancy schedules, either programmed or monitored by the building's access-control system, would automatically alter the load reduction strategy as appropriate.

3. Object oriented management information base (MIB)

Object-oriented modelling is a method of programming that closely mimics the way things are done in real life. It is more structured than previous attempts at structured programming and more modular and abstract than previous attempts of data abstraction. An object-oriented database system stores both data and programs associated with an object. This is in contrast to programs that manipulate data in semantic data model systems, where the programs themselves are not part of the database system. In recent years object-oriented databases have been proposed for many engineering and knowledge-based applications [4].

An object is the key item of information in the object-oriented representation. It represents any person, place, thing or idea in the domain of the particular application. One can describe an application's world in terms of various objects. For example, each particular area within a building can be defined as an object along with all the components needed to service the building. A class is merely a grouping or generalisation of a set of objects with some common properties. Objects may belong to several classes. A fan can be a member of the class ''air handling units'' as well as the more general class ''HVAC''. Classes may also have many objects and there is the possibility of many different relationships. A class can also have sub-classes. A sub-class is a class which represents a sub-set or ''specialisation'' of another class. It is a class in its own right and has all the characteristics of other classes. For instance, ''HVAC equipment'' could be one class with ''Pumps'', ''Fans'' and ''Boilers'' as sub-classes.

Properties are used to describe the attributes of both objects and classes and one can use any number of properties in this description. For example, a ''fan'' may have a particular power rating and size. Both of these attributes are properties of the ''fan''. While objects and classes may have specific properties, these are not limited to any one object or class. Thus other objects and classes can have the same property.

Using the object-oriented data representation as described previously, a data structure is proposed for a rule-based integrated building management system. Five main categories of data have been defined: ''Plant equipment'', ''Building'', ''Maintenance'', ''Resources'' and ''Planned events''.

3.1. Plant equipment

The plant equipment database is the largest of the five and contains a record for each item of plant equipment within the IBMS. This data is used for control and maintenance applications. Each item of equipment is represented as an object and has a number of properties associated with it. The exact properties depend on the type of equipment, some of which are plant type specific. For example, a lamp may have an average luminaire life property whilst a motor may have a phase number property. Other properties are not specific to a particular type of plant such as the description and unit cost properties. Representing this information requires the use of the class and sub-class structure with global properties defined at the parent class level and plant specific properties defined at the sub-class level. Fig. 2 illustrates this approach.

The diagram shows the class and sub-class relationship and where different properties are defined. Properties and values can be inherited from classes or objects downwards to another class or object. Individual sub-classes may have specific properties. For example, the lighting class has the additional specific properties of light level and the HVAC class has a property which stores the number of the associated air handling unit for the equipment. Finally, there may exist specific object properties which may form a further sub-class. In the case of HVAC, a fan may have a property of diameter or speed; a type of fluorescent tube may have specific light level depreciation constants.

3.2. Maintenance database

The maintenance database consists of two separate classes of data. There is a breakdown class relating to information on all reported faults and the fault class, which stores information on cumulative fault statistics (Fig. 3). The breakdown data is used to update the fault database. The maintenance database assumes that the building has a central fault reporting facility. When a fault occurs a breakdown record is created and various items of information are stored such as the fault type, the repair time and the engineer who conducted the work. Most of this information is entered after the work is done. This is facilitated by the return of a docket by the repairer when the job is completed. The historical maintenance data can be used for trend analysis and fault diagnosis.

3.3. Building database

The building database stores data relating to the design and operation of the building. Like the plant database it is structured into two sections: one storing fixed data and one dynamic. Fixed data includes properties such as

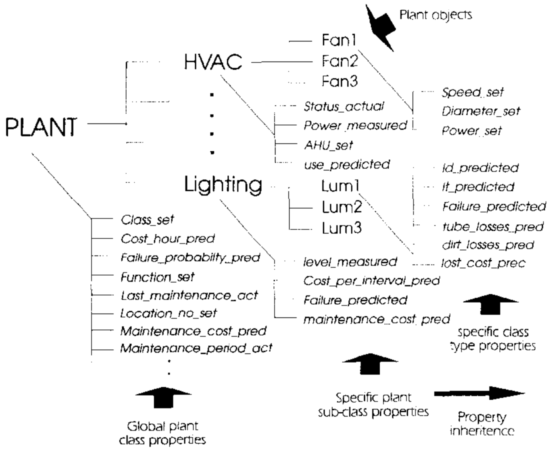


Fig. 2. Property inheritance structure for the plant database.

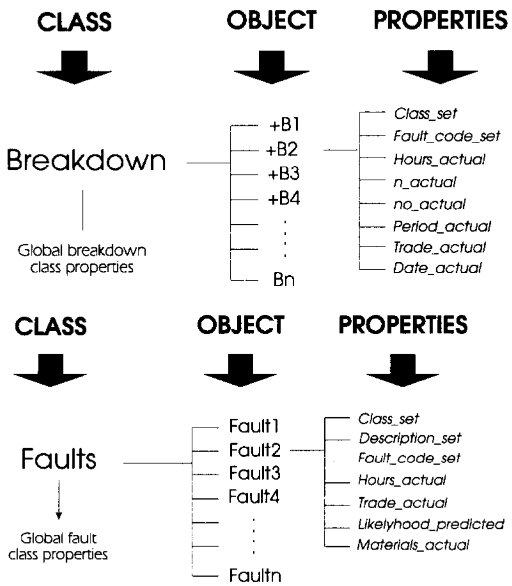


Fig. 3. Fault and breakdown data representation.

the insulation characteristics of the walls and the room sizes. The dynamic data is updated by sensors in the building and takes the form of occupancy, temperature, fire sensor data and the security status. Although room temperature sensors and, in some cases, light sensors are common in BMS the adoption of occupancy sensors has still to be widely used. A unique feature of the integrated control methodology is the use of occupancy data and occupancy prediction. The building insulation and volume data are used to model the thermal characteristics of the room for optimum start and stop control of HVAC.

3.4. Resources database

A building requires resources in many forms in order to function correctly. The "Resources" database stores this information in three sub-classes which have been defined as "Trade", "Energy" and "Stores". These sub-classes are used for the knowledge-based applications investigated in the work but do not represent a complete set. The "Trade" sub-class covers all the maintenance staff available to the estates department for breakdown or preventative maintenance work. The "Energy" class stores data on all energy used by the building, in whatever form. The "Stores" data keeps a record of all spare part stock levels retained in the building. The re-order level for stores is a non-trivial calculation for any organisation.

The resource data base is structured in a similar way to the plant equipment; the class and object properties are inherited from the main class and sub-classes. One of the main properties linking all the objects in this class is that of cost per unit resource. For example, maintenance staff have labour costs and energy is charged per kWh for gas and electricity. One of the prime uses for this data is for evaluating the running costs of the building. For example, the facilities manager could call up a graph of electricity and gas consumption for the last six months or the cost of breakdown maintenance in terms of contract maintenance labour. This has not been investigated in this work as it is implemented already on some of the more advanced BMS systems. Instead, this data has been used in the control and maintenance function rule-bases to reduce the operational cost of the building. Energy management in the building can be optimised based on the principle of majority person comfort. This means than the system aims to satisfy the environmental requirements of the maximum number of people in the building but not necessarily everyone if there are conflicting constraints. If there is a power outage, services can be shed based on equipment priority ranking in order to make best use of the available energy. The decision of whether to run the building's own generators for peak lopping is based on offsetting the generator's operation and start-up costs against the savings made in electricity and reduced tariffs. This requires knowledge of relative energy costs.

3.5. Planned events database

The planned events database is the final classification of data. This is used by the control, security and maintenance rule-bases. Each event has a classification, time, date and a text property giving a reason for the particular event. Planned maintenance is classified as a planned event. With this information, the IBMS can schedule resources and ensure that the plant and associated equipment are automatically deactivated at the repair time. The building diary database allows the occupants to inform the estates department about the planned usage of the building. Prior knowledge of abnormal out-of-hours occupation allows the control knowledge-base to schedule services such as lighting and heating. This overrides the zone controller's occupancy monitoring and prediction methodology thus allowing services to be scheduled for out of hours activity. It also allows maintenance to be scheduled at times which cause least inconvenience to the occupants of the building.

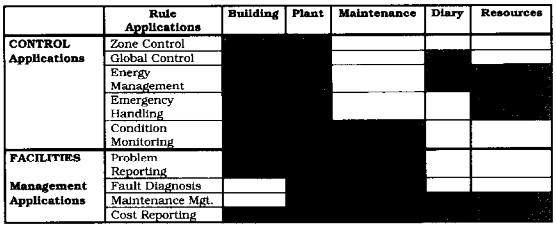
3.6. Rule description

The IBMS is described in terms of objects. The rules provide the ability to reason on the objects within the knowledge domain. Rules contain the knowledge necessary to solve particular domain problems. The rules can be written in the following form.

```
If          condition_A is True
            & condition_B is True
            & etc...
⇒           Hypothesis_X is confirmed
            & do action_1
            & etc...
```

Rules are symmetric, i.e. they have no inherent direction in them. This means that the rule can either be processed in the forward direction by forward chaining events or in the backward direction by backward chaining events. The symmetrical property of rules means that there is no need to write one set of forward chaining rules and another set of backward chaining rules. All property values used explicitly in the left-hand side conditions, or the right-hand side actions of a rule, are called data. Hypotheses which are also data are referred to as sub-goals. When a rule is processed it is said to have been ''fired''.

If all the conditions on the left-hand side are evaluated to true, the hypothesis is then set to true. The right-hand side actions are only executed if the hypothesis is evaluated to be true. In contrast to the other two parts of a rule, right-hand side actions are not required. They are a series of consequences of the rule being fired which are executed as soon as the rule is verified. There may be any number of right-hand side actions. Rule actions can be used to reset the value of the rule's hypothesis to ''unknown'' and force the rule to be re-evaluated. This means that the rule continually backward chains to itself until it is proved false. Every rule has an inference priority which determines the order in which it is processed when forward or backward chaining is not in operation. In this way, rules which diagnose important events such as a fire or loss of power can be given a higher processing order than rules which handle less important situations.



	Rule Applications	Building	Plant	Maintenance	Diary	Resources
CONTROL Applications	Zone Control	■	■			
	Global Control	■	■		■	
	Energy Management	■	■		■	■
	Emergency Handling	■	■			■
	Condition Monitoring	■	■	■		
FACILITIES Management Applications	Problem Reporting	■	■	■		
	Fault Diagnosis		■	■		
	Maintenance Mgt.		■	■	■	■
	Cost Reporting	■	■	■	■	■

Fig. 4. Knowledge-base data class interaction.

3.7. Knowledge-bases

A collection of rules intended to perform a common function are defined as a knowledge-base. Two main knowledge-bases have been defined for use within a rule-based IBMS. The first is the building control knowledge-base which co-ordinates the control of all the building services. It ensures that the required environment is maintained in all parts of the building, depending on an area's function and activity, for an efficient operating cost. One part of this knowledge-base is processed simultaneously on each of the building's outstations whilst another part is processed on the central control computer. The control knowledge-base is also responsible for handling emergency situations such as the loss of power, or a fire, along with error reporting and condition monitoring. The control knowledge-base is processed continuously and without interaction with the human operator.

The second knowledge-base is concerned with facilities management functions within the building. This knowledge-base requires interaction with the IBMS operator and is processed only when required by the operator. One of the main features of this knowledge-base is to provide on-line fault diagnosis and decision support for breakdowns and the scheduling of maintenance work. Both of these knowledge-bases interact with the classes of data outlined in this section. Within each knowledge-base rules have been defined to perform specific functions as shown in Fig. 4.

The functions are classified by the classes of data on which they operate and in what part of the IBMS they are processed, i.e. the set of rules which only operates on the "Building" and "Plant" classes of data are defined as zone control rules. The inference engine links the "intelligence" stored as rules with the knowledge in the form of a database. A prototype system has been built to investigate some of the ideas proposed in this paper. The specific classes of data required for the KBS have been used to structure an object-oriented database.

4. Case study of knowledge-based systems

There are many commercial KBS shell software packages available on the market. One such system, Nexpert Object, was used to investigate knowledge-based building management systems [5]. A prototype has been built using Nexpert Object and Microsoft's Excel spreadsheet package. Excel is an ideal tool for a prototype database of this nature owing to its advanced facility to form dynamic cell links between sheets. The spreadsheet provides a gateway between the data acquisition and the knowledge-base application. Both Nexpert and Excel run within the Microsoft Windows 3.x environment. They both support the Windows 3 direct data link (DDL) feature as well as SYLK database retrieval format which is a derivative of the structured query language (SQL) standard. Nexpert can automatically read in an Excel file from disk and use it to generate an object-oriented data structure, which is then processed by the rule-base.

A simulation was conducted in consultation with engineers at Dunwoody and Partners to predict possible energy savings using a building services design package called HevaStar. This is a suite of software packages for building services engineers to use for computer aided design and design evaluation. This package has been widely used by the engineers at Dunwoody for several years. Two programs were used: "HLOSS" which estimates the building's thermal energy loss and "ENERGY" which calculates the annual heating energy consumption of the building. This is done by firstly calculating the design heat loss of the building and then by using a version of the degree day method, modified to allow for permissible solar, lighting and people heat gains using techniques from the UK's CIBSE Energy Code Part 2(a). The largest building on the Brunel campus was chosen for the simulation which considered heating, lighting and ventilation savings.

A hierarchical approach is proposed in which an area's environmental control is achieved by energy management rules running on intelligent outstations. The central IBMS control workstation runs global control rules which have the ability to override the outstation control. Occupancy monitoring and prediction are used in conjunction with the rules which make intelligent decisions on the control of HVAC and lighting. The ideas are illustrated using case studies for both zone and global control functions.

4.1. Rule-based control structure

An IBMS offers the scope for some advanced control strategies. More information is available, not only on the system under control but also on related systems, which can be used for integrated control functions. This information is used to provide improved energy management and emergency handling features. Three distinct areas of control have been identified:

1. Global control strategies
2. Zone environmental control
3. Local plant control loops

These three control levels are illustrated in Fig. 5.

The plant is controlled by local controllers consisting of relays or power electronic switches. Examples of these include PID control loops for heating and thyristor phase angle controllers for lighting. The zone control strategy has the authority to override the PID control loops and ensure the optimal environment for the occupants of the building. A local zone controller is proposed to provide more intelligent environmental control than provided by current systems by tuning the environmental control to the exact usage of the area. This control level uses information from the central IBMS control system along with data from the local sensors. Similarly, when required, the global control level strategies can override the zone control. This enables the IBMS to handle emergency situations such as load shedding and building-wide energy management.

Within the context of a knowledge-based IBMS a rule-based control system has been investigated which implements (1) and (2) above whilst integrating with the existing lower level autonomous control. Several rule-bases have been developed for zone and global energy management within the building and a prototype zone controller was designed and evaluated.

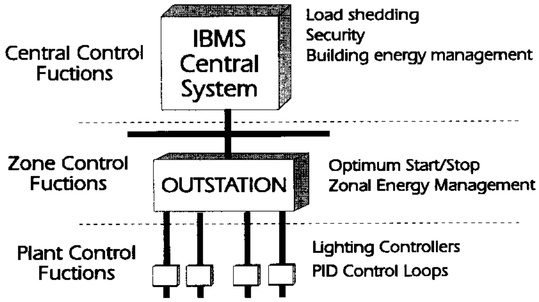


Fig. 5. Global and zone level control functions.

4.2. Global control

Some global control functions would not be practicable in a non-integrated building management system. Such applications include energy management in the form of load control and emergency situation handling such as load shedding. Existing BMS control functions include algorithms for load management such as load cycling, load balancing and demand limiting [6]. The rule-based approach does not try to replace these functions but rather to enhance them by optimising their performance.

Recent changes in local electricity metering in the UK will mean that the IBMS will have more information on energy consumption throughout the building. Large consumers with a maximum demand greater than 1 MW can buy their electricity from any licensed supplier; this is called second-tier supply [7]. The minimum requirements for this change are in the metering technology and the methods for meter readings. The introduction of this increased metering would enable an IBMS to know what items of a plant are consuming at any time. This would permit a building management system to have far more control over energy management with electricity load control.

As the cost of electricity can vary very significantly over a 24 h period there are clear benefits in being able to limit demand when generating costs are high. With direct control of suitable loads, such as heating and lighting, a rule-based system can reduce peak costs by temporarily shutting down loads to reduce consumption.

Besides reducing the running costs, the building control system must be able to handle the possibility of supply failure. This actually happens more often than one would suppose. There are certain loads in the building that should not be interrupted such as sensitive electrical equipment and emergency lighting. Provision is usually made for such loads using uninterruptible power supplies (UPS) and standby generators. For example, in the Lloyd's building, if the main incoming 11 kV power supply is lost, all essential loads are immediately transferred to the 250 kW UPS system whilst the two 1.75 MW standby generators are started. These generators take about 20 s to get up to speed. All non-essential loads must be shed until the total load demand can be supplied by the available power supply capacity. This is conducted by the Johnson's BMS and supervised by the control room operator. Methodologies exist for optimum load shedding in large power systems [8,9]. However, in building management systems the actions to be followed in the event of an outage are usually pre-programmed into the BMS at the commissioning stage. Individual loads are often allocated a set priority level, and when a power outage occurs, loads are shed in order of least priority. In reality, the best loads to be shed will depend on the time of day and what is happening in the building. What is required is an intelligent control system which strategically prioritises the loads in the building for optimum occupant comfort during supply outage situations.

Instead of just using pre-programmed load priorities this work has investigated the use of a dynamic system of priorities which are based on many factors such as area usage, occupancy, time of day and real-time environmental conditions. These priorities, which are set by rules running on the central control system, make use of information gathered from outstations throughout the building and communicated via the building's data-bus.

4.3. Occupancy prediction

For the prototype controller, occupancy levels were stored in the controller's memory at 15 min intervals with a moving window of 21 days. Prediction is achieved by looking up the value for the time to be predicted based on average occupancy for the previous three weeks at that time and day. If the prediction time does not correspond with a stored value it can be calculated by means of statistical interpolation. This prevents the prediction from being misled by a one-off change in occupancy. If the trend continues, the predictor will adapt after three weeks. For example, if an area is always occupied from 9 a.m. to 5 p.m. and the use suddenly changed to 8 a.m. to 4 p.m., the predictor would fully adapt to this change after three weeks but a single deviation from the normal pattern would not cause any change. The adaptation time can be set to suit the functionality of the area under control. This control pattern can be overridden by information obtained from the building's diary database to allow for schedules meetings and public holidays for example.

4.4. Global controller

The global control knowledge-base, which is run on the central IBMS controller, is structured into separate rule-bases which are fired in an order of priority. These rules provide global energy savings and emergency handling features. The highest priority rules are suggested if load shedding is required and loads are shut down in the order of load priority until the buildings electrical load equals the supply capability. The order of priority for loads is a dynamic variable which is determined by an area's function, occupancy and the time of day. If no further load shedding rules can be suggested the "engage loads" rules are suggested; loads are then engaged, if required, providing the supply capability is sufficient. The final group of rules are included to detect energy wasting areas within the building such as dormant rooms and to shut down unnecessary loads to save running costs.

To enable the knowledge about the control process to be generic to the building and any structural changes than may take place within it these rules must be written so that they are independent of the number of the outstations. They operate on the "Building" class and make extensive use of pattern matching and strategic resetting of the rule hypothesis.

4.5. Global control override rules

The rules described in this section have hypothesis objects which are automatically reset and evoked at regular intervals. Through the use of class pattern matching they operate on all "Building" and "Plant" objects irrespective of the number of objects in each class.

There are many areas which are not controlled by an individual zone controller such as corridors and wash rooms. These areas may not be continuously occupied and thus a self-tuning zone controller would have difficulty in predicting occupancy along with the pre-heat and optimum stop times. The control of these areas is, therefore, linked to the activity of associated areas within the building thus ensuring that these areas are always at the required environmental conditions should they become occupied. Thus a wash room will be defined as "quiet" even though it is not occupied if there is occupancy in the rooms near to it. The room is controlled by zone controllers as described previously but without the self-learning occupancy prediction feature; the occupancy prediction is down-loaded to the controller from the global control system [2]. For example, the following rule sets the control mode for areas of the building defined as "corridor".

```
if      |BUILDING|.description_set= `corridor '
        & |BUILDING|.mode_status= `off '
        & ||BUILDING||.mode_status is not ( `on ',  `start ')
        & |BUILDING|.floor_set=||BUILDING||.floor_set
        & MAX[|BUILDING|.no_set]
⇒       Related_area is confirmed
        &  `start ' is assigned to |BUILDING|.mode_status
        & reset Related_area
        & do Related_area
```

---

[2] This does not affect the control of lighting which remains the same as for a standard zone. The use of presence detectors to turn lighting on and off in areas of the building which are occupied albeit not continuously is firstly annoying for the occupants and secondly can be more expensive than leaving them switched on owing to the excessive wear on the luminars owing to frequent switching on and off.

The first pattern matching finds the set of objects belonging to the class "Building" that are defined as "corridors" and whose control mode is "off". The second independent pattern matching, indicated by the double lines, finds the set of objects whose mode is either "on" or "start". The first set is further reduced to those objects which have the same "floor" property value as any of those objects in the second set. These are the objects representing rooms in the building that are in the "off" control mode whilst another area on the same floor is either in pre-heat or occupied mode. The pre-heat mode is when the heating/cooling system is attempting to get the environmental conditions up to the required settings for the area to be occupied. These areas are switched to "start" mode. This has the effect of keeping them in continuous pre-heat mode until they become occupied then their controller will switch to the "on" state. A maximum function is used to select just one object from the set and as the actions of the rule reset the rule's own hypothesis the rule is continuously fired until all the areas meeting the condition of the existential pattern matching are switched to "start". The rule will then fail as by definition of the rule's function no objects with the same value "floor-set" property will simultaneously meet the two pattern matching conditions. A similar rule switches areas from "on" to "stop" if all the areas on the same floor enter the "stop" or "off" states.

4.6. Global energy saving rules

The study includes the option of running the BMS in an "economy" mode, whereby the rule-based global control system can further reduce energy consumption within the building. Some of these features, such as load control and load balancing, are incorporated in existing energy management systems. The aim here is to show that the existing algorithms can be assimilated in a rule-based methodology. These features can be implemented in such a way that they cause less discomfort to the majority of the occupants whilst still saving energy.

At certain times of the day HVAC and lighting can be reduced in sparsely occupied areas of the building to save energy. In areas which are defined as "quiet", the HVAC set points are reduced before the optimum stop time thus saving energy and causing a slight discomfort to only a small number of people. This is achieved by the dormant mode control rules which take the form shown below.

```
if      BUILDING.mode_status is 'Economy '
        & |BUILDING|.activity_actual is 'quiet '
⇒       Economy_control is confirmed
        & Building.temp_min_set is assigned to |BUILDING|.temp_set
        & Building.light_min_set is assigned to |BUILDING|.light_set
```

This rule makes use of the "Building.mode_status" property, the value of which is set by the operator as being "normal" or "economy". This property is used to enable or disable the economy rules. The property "Building.temp_min_set" stores the minimum set values for the economy mode. This is down-loaded to all zone controllers which have a "quiet" activity level. If the economy mode ends, or if the activity in these areas changes, the following two rules down-load the zone's normal set points.

```
if      Building.mode_status is 'Normal '
⇒       Normal_control is confirmed
        & |BUILDING|.temp_normal_set is assigned to |BUILDING|.temp_set
        & |BUILDING|.light_normal_set is assigned to |BUILDING|.light_set

if      Building.mode_status is 'Economy '
        & |BUILDING|.activity_actual is not 'quiet '
⇒       Normal_control is confirmed
        & |BUILDING|.temp_normal_set is assigned to |BUILDING|.temp_set
        & |BUILDING|.light_normal_set is assigned to |BUILDING|.light_set
```

Other forms of energy savings incorporated in the global control rules are load control, load balancing and peak lopping. The load control technique relies on the fact that the heating, ventilation and air conditioning plant is sized for design conditions which may only apply for a few days each year. For the remainder of the year the plant is running below its design capacity. Although conventional temperature controls may be used to regulate the amount of heating or cooling energy coming into the building, they do not necessarily do anything to limit the amount of air being circulated via a fan-driven ventilation system. As long as the fan is running, electrical energy is being consumed just in moving the air around the building. To save electrical energy, load cycling switches the plant off for a percentage of the time. Switching a fan off for 10 min h^{-1} saves 16.7% of the electrical energy driving the fan [3]. This saving is made at the expense of the occupant's comfort but, providing the limits to which load control operates are carefully chosen, the effect should be virtually unnoticeable to the occupants.

The air handling units selected for load control supply areas of the building where the actual environmental conditions are near to their maximum set temperature values. This differs from load shedding in that loads are being alternated rather than shut down. This switching must be updated much faster than the re-allocation of load priorities and subsequent changes described later in the section on load shedding. Also, unlike load shedding, the autonomous control operation of the zone outstations is only overridden and not completely suspended. The following describes the set of rules which handle load control for the air handling unit fans.

```
If      Building.mode_status= 'Economy '
        & |BUILDING|.mode_status= 'on '
        & |BUILDING|.temp_measured ≥ |BUILDING|.temp_set ×0.9
        & ||HVAC||.location_influence_no_set=|BUILDING|.location_no_set
        & ||HVAC||.class_set= 'Air handling units '
        & ||HVAC||.time_off_actual ≤ ||HVAC||.max_time_off_predicted
⇒       Ahu_load_control is confirmed
        & 'stop ' is assigned to |BUILDING|.mode_status
        & 0 is assigned to ||HVAC||.control_status
```

In the load control rule shown previously, pattern matching is used to find the areas in the building where the temperature is approximately equal to the maximum pre-set limit. The sub-set of HVAC objects are found which serve these areas and the set is further reduced to those air handling units which are currently running. The status of these areas is set to "stop" which is used to signify a temporary shut down. When the heating level drops to the minimum set point, the heating can be re-engaged under zone control (in the same way that an optimum stop cycle is aborted if the occupancy is still greater than one when the pre-set minimum temperature is reached). Therefore, a further rule is not required in the global control knowledge-base to re-engage the loads. The rule also checks that the air conditioning is sufficient for the number of occupants in the area using a method to calculate the optimum value of the "max_time_off_predicted". This calculation is based on the current EEC guidelines for ventilation requirements in buildings. Alternatively CO_2 monitoring could be used but this would incur the extra cost of installing CO_2 sensors.If N_{ac} is the minimum number of air changes required per hour, Q_f is the fan's rated air supply and V is the room's volume, the property "max_time_off_predicted" (in minutes) is calculated as follows:

$$N_{ac} = Q_f \times 60 \times 60/V \times (60 - \text{max\_time\_off\_predicted})/60$$

$$\Rightarrow \text{max\_time\_off\_predicted} = 60 - 60.N_{ac}/(Q_f \times 60 \times 60/V)$$

---

[3] This does not necessarily save any of the heating or cooling energy required to meet the set environmental conditions. If by switching the fan off for 10 min the zone temperature changes by 1°C, additional heating or cooling energy is then needed during the "on" period to get it back to the required temperature. This extra energy would be roughly equal to the heating or cooling energy saved.

The required number of air changes is calculated by,

$$N_{ac} = 0.001 \times Q_c / H$$

where H is the room's height and Q_c is the required air flow in $\mathrm{l\,s^{-1}\,m^{-2}}$ (floor area) for comfort calculated by:

$$Q_c = 10 \frac{G}{C_i - C_o} \frac{1}{\epsilon_v} \tag{1}$$

where: Q_c is ventilation rate required for comfort ($\mathrm{l\,s^{-1}}$); G is sensory pollution load [olf]; C_i is perceived indoor air quality, desired [decipol]; C_o is perceived outdoor air quality at air intake [decipol]; and ϵ_v is ventilation effectiveness.

For example, the main lecture theatre at Brunel has a floor area of $315\,\mathrm{m^2}$, a volume of $1150\,\mathrm{m^3}$ and a maximum seating capacity of 200 people. The ventilation fans for supply and extraction are rated at 4.3A for a three-phase UK mains supply and supply air at $4\,\mathrm{m^3\,s^{-1}}$. If the theatre is only occupied by 70 people, the required ventilation calculated using (1) would be $1.01\,\mathrm{l\,s^{-1}}$. This means that the theatre would require one air change per hour and the fan's duty cycle would be 0.08. This would save 5.7 kW of electricity per hour.

Load control does cause additional wear on the plant because of the increased starter operations, increased strain on the fan motors and fan belt wear. While the latter is true, most manufacturers of air handling units rate their products for much greater frequency of operation than is imposed by load control. The energy savings offset the costs of additional belt replacement many times over. However, to avoid extra maintenance, two speed fans can be employed and the fans switched from high speed to low speed thus reducing the adverse effect of the sudden reduction in air movement.

Load balancing can be integrated with the load control rules. This involves the temporary and systematic switching off of different electricity consumers to reduce the peak electricity demand. Large electricity consumers are charged a tariff based on the peak demand. This is because the installation must be of sufficient capacity to meet this maximum demand and hence it mostly reflects the overheads in terms of the supply installation. Peak lopping is designed to reduce this peak as far as possible. Fig. 6 shows a typical demand for a building during the day. A peak often occurs mid-morning or mid-afternoon. If this peak, which may only last for a few minutes, is reduced, the fixed charge tariff would also be reduced.

In conventional systems the loads are assigned a weighting in terms of their size and the load balancing algorithm arranges the start and stop periods for each load so that, taken over the maximum cycle period, the total load at any one time is as close to the average as possible. One cannot assume that all the loads are the same or that the thermal time constants of the areas they control are similar. For example, in the worst case the

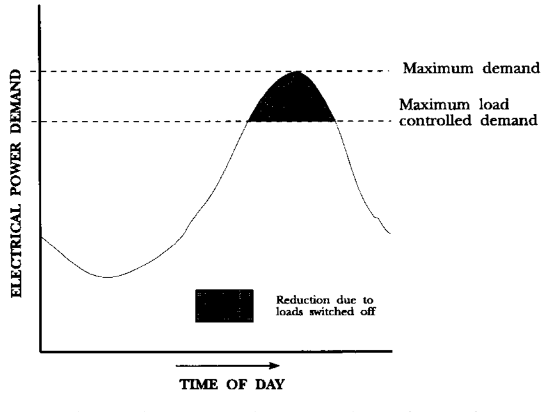


Fig. 6. Diagram showing power demand control.

loads may consist of one 100 kW load and twenty 4 kW loads. Similarly, there may be one large area with a pre-heat time of $1\frac{1}{2}$ h and others which require only 20 min. Within the rule-based control system, the load balancing algorithm can be incorporated by the addition of a single rule. This rule is a modification of the load control rule shown previously. Where indicated by the dotted lines the rule is exactly the same as the load control rule but incorporating five extra condition clauses and two extra action clauses. Also, the pattern matching reduces the main sub-set to one object which is shut down by the rule actions unlike the load control rule which can operate on a set of eligible objects simultaneously. The rule resets its own hypothesis and calls itself if the condition clauses are all true. Thus the hypothesis is proved false when all the eligible loads are shut down. The rule is shown below.

```
If................
& |||BUILDING|||.mode_status = 'stop', 'on'
& ||HVAC||.location_influence_no_set = |||BUILDING|||.location_no _set
& ||||HVAC||||.class_set = 'Air handling units'
& SUM[||HVAC||.power_predicted]
≥ 1/2 × SUM[||||HVAC||||.power_predicted]
& MIN {ABS {SUM[||HVAC||.power_predicted]
− 1/2 × SUM[||||HVAC||||.power_predicted]
−||HVAC||.power_predicted} }
⇒ Ahu_load_balance is confirmed
& ..................
& reset Ahu_load_balance
& do Ahu_load_balance
```

The first three additional clauses of the rule find the set of air handling units which control areas which are either in the "on" or "stop" modes. This set of "HVAC" equipment is indicated by the four lines. The fifth additional clause checks that the sum of the power for all the engaged air units is greater or equal to half of the total power consumption for all the air handling units not supplying a dormant area. This prevents more fans being shut down, even though it is economic to do so, if more that half the maximum theoretical demand is temporarily shut down. If all loads which are economic to be shut down were shut down, this would cause a dip below the mean and thus a greater peak above the mean when they were reactivated. The addition of this clause controls the peak demand such that it cycles about the mean value as closely as possible and prevents excessive peaks as illustrated in Fig. 7.

The final additional clause reduces the set of eligible loads to be shut down, indicated by the double lines, to the one that brings the total demand to as close as possible the mean value. This is done by finding the single object that gives the minimum absolute value when its power rating is deducted from half the total theoretical power minus the engaged power for the air handling units. This clause is given as a condition to the rule since if no loads meet this criteria no improvement to the load balance can be achieved.

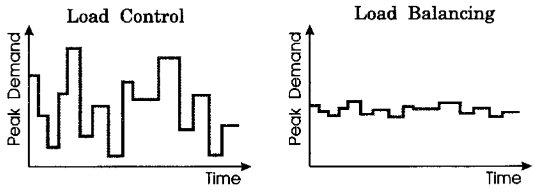


Fig. 7. Peak demand profile for balanced/unbalanced load control.

5. Conclusions

Integration of building services should reduce costs in two ways: firstly by unifying the various wiring to the control systems (possibly with separate but interconnected circuits for fire alarms); and secondly by standardising components such as switches, controllers and sensors. Currently, buildings incorporate at least four layers of wiring: voice, security data, environmental control and word processing. To reduce this in the future, the move will be towards the building data-bus. A common building data-bus should bring down the cost of controlling building services and make complex building management systems more widely available. ATM network technology is proposed as the solution for unifying building communications. The properties of an ATM network make it ideal for the multi-media forms of data within buildings such as voice, data and video. A methodology has been proposed to use the integrated data now available from a single BMS data bus to improve the BMS control function through the use of a rule-based control system.

Energy savings can be achieved by incorporating a self-tuning occupancy predictor into the zone controller and by using rules to control the environment within the building for maximum occupant comfort at minimum cost. The full energy saving potential is often not obtained from current energy management systems as the users of such systems lack the time required to reset set points and occupancy schedules. The rules enhance the control in the following ways.

- The optimum start and stop cycles are tuned to fit the expected occupancy patterns using a mathematical thermal model of the area. If the model's prediction is incorrect, rules exist to modify the model. It was found by comparing the results of experiment with the predictions of the thermal model, that the optimal start and stop times could be predicted to an accuracy of 3% for external in the range 3–20 degrees. The results show a good correlation despite the simplifications involved in the mathematical model. However, these results were obtained during a two week period, during which large variations in external temperature did not occur. Nevertheless, the self tuning aspect should keep the system in tune under varying conditions.
- To prevent the controller from making incorrect decisions on environmental control, a combination of actual and predicted occupancy is used. This prevents the controller switching the lights off when someone leaves the room for a brief period or when the area's occupancy suddenly changes from the predicted pattern. In all cases, the controller errs on the side of caution.
- It has been predicted by computer simulation that electricity savings of up to 20% would be potentially possible for lighting and heating by tuning the control of building services to the use of the building.
- Rules are included to prevent excessive wear on equipment caused by too frequent switching and to control the environment in areas not continuously occupied by relating their activity to other areas of the building.
- The global control system overrides the occupancy prediction when an area is known to be occupied and, if required, automatically takes the plant out of service prior to maintenance or routine inspection.
- Emergency situations, such load shedding, are handled with least inconvenience to the majority of the occupants using a system of variable load priorities.
- It has been shown that current energy saving schemes such as load control and load balancing can easily be incorporated into the rule-based control methodology.

An object-oriented data structure has been proposed in which all the key information required by the rules is classified into distinct classes. In practice, object orientation design takes longer to develop than conventional structured language implementations. The advantage lies in the subsequent modification and maintenance. The object orientation is important at the global-control level and for the facilities management knowledge-base. Here it would be impractical to write rule-bases for each application. The rules have been written around classes of equipment and objects which are described in terms of properties. This detaches the knowledge, coded as rules, from the actual data describing the building and its systems. The rules proposed are valid whether there is only one zone controller or several hundred. Similarly, within a class of equipment, such as air handling units, the rules are valid if a particular air unit has three filters of 33 filters. Modification of a particular object can take place without requiring major changes to the knowledge-base. Only the rules and methods relating to the object required changing. This is an important quality for the commercial viability of such a system, as it would be impracticable to write custom rule-bases for every application.

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