Performance Prediction Tools for Low Impact Building Design

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ABSRACT
IT systems are emerging that may be used to support decisions relating to the design of a built enviroment that has low impact in terms of energy use and environmental emissions. This paper summarises this prospect in relation to four complementary application areas: digital cities, rational planning, virtual design and Internet energy services.

KEYWORDS
Digital cities, rational planning, virtual design, Internet energy services.

INTRODUCTION
The energy and environment domain is inherently complex and, consequently, conflicting viewpoints abound, proffered solutions are typically polarised and consensus is impossible to attain. Indeed, the different vested interests serve only to render vacuous the relationship between sustainability and energy action. This unacceptable situation gives rise to three fundamental engineering challenges: how to consider energy systems in a holistic manner in order to address the inherent complexity; how to include socio-environmental aspects in the assessment of cost-performance in order to improve overall performance; and how to embrace inter-disciplinary working in order to derive benefit from the innovative approaches to be found at the interface between the disciplines.

An effective way to address these challenges is to help stakeholders to look beyond their preconceptions, to see the real state of the world and differentiate between the promising and the possible. An essential element in promoting the rational use of energy is that decision-makers (including citizens) be given access to relevant sources of information. In the present context, these include energy demand profiles, the characteristics of potential sources of supply, and the outputs from modelling studies to assess the benefit and impact of alternative options. However, indications are that, at present, comprehensive information is rarely in the hands of those who require it, and the use of modelling in strategy formulation is virtually unknown. This paper considers four complementary applications for energy and environment modelling that have the potential to radically change this situation:

- digital cities—entailing the monitoring of fuel use and availability in order to identify areas of concern and assist with the identification of options for change;
- rational planning—entailing the matching of energy demand and supply in order to assist with the deployment of new and renewable energy systems at all scales;
- virtual design—by which energy systems simulation may be used to conjecture and test specific designs prior to construction; and
- energy services—entailing the Internet delivery of 'up-to-the-minute' information to professionals and citizens, and the enactment of dynamic demand side management at the aggregate scale.

DIGITAL CITIES
Figure 1 summarises the digital city concept. Acting in partnership, utilities, local authorities and others feed information to a shared database covering some geographical area of interest. To accommodate the temporal and scope mismatches between its component parts, the database is distributed, with Internet-resident control agents acting to recover suitable integrations when enquiries at the aggregate scale are submitted (e.g. regional fuel use, gaseous emissions, renewable energy resource availability *etc*). These data may then be analysed in order to provide relevant and up-to-the-minute information to a range of possible recipients, from policy makers, through planners and designers, to citizens. To assist with interpretation, a Geographical Information System (Clarke and Grant 1996) may be employed to overlay the energy and environment information on conventional types of information such as street layouts or power cable routings. To assist with policy formulation, an energy model is included to enable an appraisal of options for change. Where an option proves beneficial, its predicted fuel use may be returned to the database to be held alongside the present fuel use data. This enables the side-by-side display of information relating to the present and future cases in support of inter-comparisons before deployment decisions are taken.

EnTrak (Clarke *et al* 1998, Evans 2000) is an example of an existing system that seeks to deliver this functionality. The system offers constant monitoring and integration of fuel data relating to properties and RE schemes, consumption & supply classification, trend analysis and targeting, and the assessment of cost-effectiveness. It is foreseen that the extent to which the system can provide comprehensive planning and energy management support is limited only by the availability of high quality data of adequate resolution, or the ability to generate this by simulation at the time of need. The capacity exists within *EnTrak* to record time-based output figures from RE conversion systems of any kind. Such systems are, of course, still few in number. To investigate future scenarios, in which development is more intensive, two approaches are possible: where a system already exists, which may be regarded as prototypical, it can be duplicated in a new location; or the output of hypothetical systems may be modelled as a function of climate and other variables using simulation techniques.

EnTrak is built upon a distributed, SQL database architecture using JDBC technology (Sun 2002) to achieve database connectivity. Web-enabled analysis modules operate on this database to produce information tailored to the requirements of the various users. For example, Figure 1 depicts the fuel use and related gaseous emissions for a portion of a city. Such information can support a range of activities, from energy action planning, to the wider participation of citizens. By modelling proposed measures prior to their deployment, alternative options can be compared in terms of relevant criteria, including the impact on the energy supply system and the mitigation of greenhouse gas emissions. Furthermore, the impact of previous actions is implicit within the monitoring process so that schemes with a poor return can be quickly discarded and those with a high return retained.

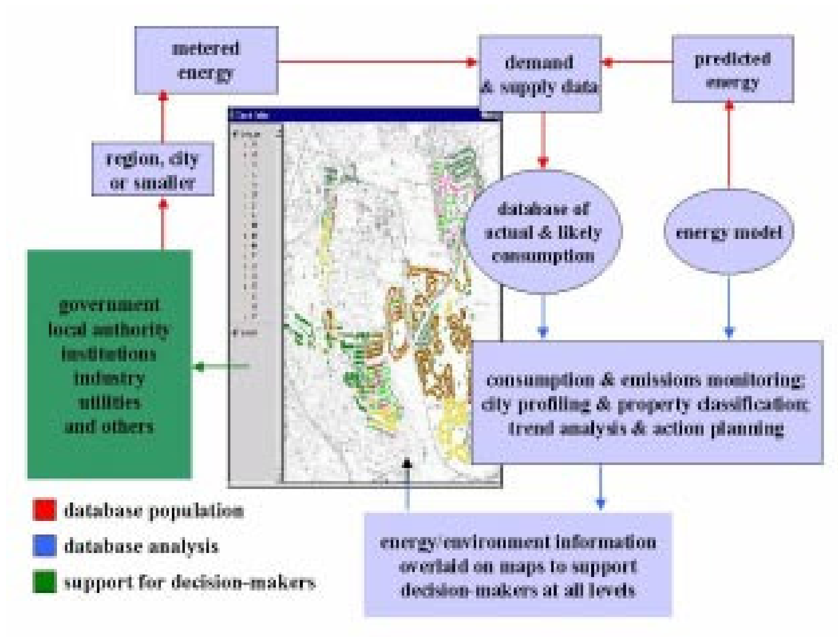

Figure 1: The digital city concept.

The central and crucial requirements of such IT systems are database construction and maintenance. In the former case, two data collection methods are extant: electronic data interchange (EDI) and direct monitoring via the Internet. EDI entails the regular exchange of data via computer files adhering to a pre-agreed format. It is a typical interaction mode between large organisations such as local authorities and utilities. Direct monitoring requires the embedding of sensors throughout the monitored estate and the connection of these sensors to a local electronic gateway device giving access to the Internet. This approach (see later) is suitable for application at all scales—from a home to a power station.

RATIONAL PLANNING

Future cities are likely to be characterised by a greater level of new and renewable energy (RE) systems deployment. Maximum impact will be achieved when such systems are used to offset local energy demands in contrast to current philosophy dictating the grid connection of large schemes (i.e. distributed generation). To assist with the integration of such systems at the local level, it is important to utilise energy efficiency techniques to reduce energy demands to magnitudes that present a favourable load for the new and RE systems being targeted. The technologies to be employed therefore fall into two categories:

- demand reduction systems: mainly passive in nature and used to reduce peak demands and reshape the demand profile, e.g. advanced glazing systems to maximise daylight capture and distribution, smart control to eliminate waste, and solar thermal collectors to offset heating capacity; and
- power supply systems: mainly active technologies, which convert captured energy into electrical power and heat for use to meet the building's reduced demand.

The *Merit* system (Born 2001, Smith 2002), for example, is built upon the interacting components as shown in Figure 2. In use, the first task is to specify the climate context of the appraisal. This is achieved by selecting from a database of standard climates or by importing site-specific weather data. The second task is to establish a set of demand profiles for the problem in hand. This set can be established to represent a problem at any scale: appliance, building, city district or national region. Large-scale sets may be produced by combining specific profile types after manipulation to reflect the scale. Where a monitoring programme has produced appropriate demand data for a specific site, this can be imported.

The next task is to select possible supply technologies to meet the demands. First, energy systems (renewable or otherwise) are selected from a model library or, where performance data exists for a specific technology, this can be imported. Each technology can be held individually or combined with other types to establish a combination supply. Second, an auxiliary supply system may be selected, comprising battery storage, a connection to the electricity supply network or a back-up generator.

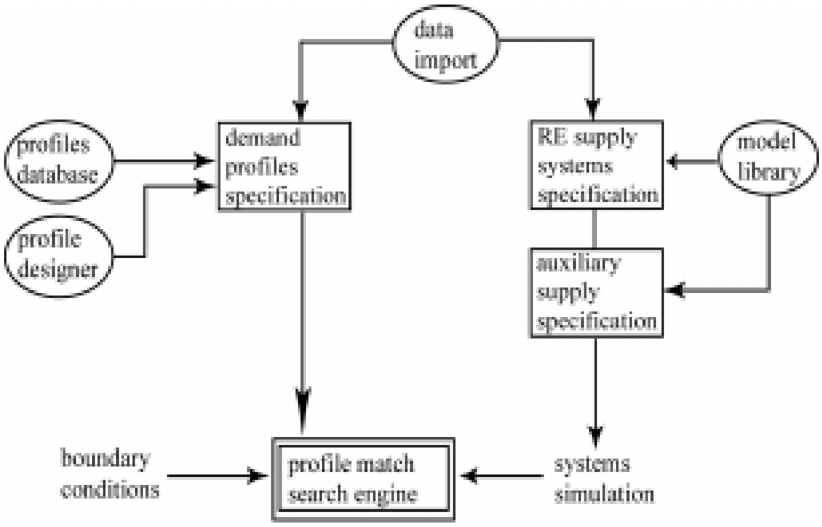

Figure 2: The rational planning concept.

Merit is now ready to conduct an automated search in order to identify those combinations that best match specified search criteria. Figure 3 illustrates a possible outcome. The first graph shows the demand superimposed on the supply to illustrate the temporal match. The second graph shows the associated energy residual, the portion above the x-axis representing a deficit. The third graph is active when an auxiliary system is selected and details its performance and duty cycle. The tabulated statistics include an inequality metric (to indicate the quantitative fit) and a correlation coefficient (to indicate the dynamic fit). The energy surplus or deficit is also displayed. In this way, a user can call for the identification of the best supply match per individual demand or best supply match overall. This search performance benchmarks each match before initiating a search ordering process, which presents possible matches in order from best to worst. Systems such as *Merit* allow energy managers, planners and designers to appraise the potential for new and RE systems deployment at an early stage in the design process. This allows site-specific technologies to be identified and their required capacities to be established. The stage is then set for a detailed, integrated performance appraisal of viable schemes. This is the subject of the next section.

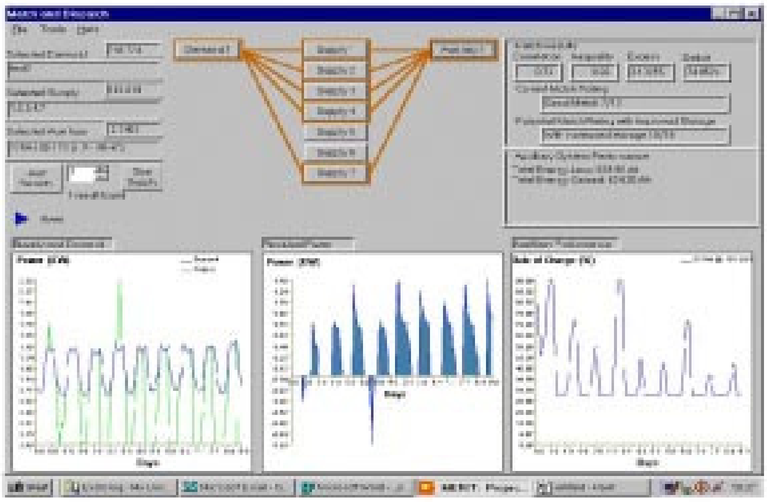
Figure 3: Matching supply to demand using *Merit*.

VIRTUAL DESIGN

Because the built environment consumes the greater portion of total delivered energy and is responsible for most of the avoidable CO_2 emissions, many initiatives are focused on this sector. However, buildings are complex, and in the absence of a means to predict the performance benefit of proposed measures, such initiatives will probably fail. Modelling methods, when embedded within the building design process, allow the industry to pursue new designs and refurbishments that: conform to legislative requirements; provide the requisite levels of thermal, acoustic and lighting comfort; attain high indoor air quality standards; embody high levels of new and RE technologies; incorporate innovative solutions; and lessen environmental impact.

It is widely accepted that integrated modelling defines a new best practice approach (CIBSE 1998) to energy systems design because it allows designers to address important new challenges such as the linking of energy, the environment and health. In use, the approach requires the gradual evolution of a problem's description, with performance outputs becoming available at discrete stages as relevant information becomes available. Consider the *ESP-r* (Clarke 2001) based modelling process of Figure 4, which indicates a possible computational approach to design.

a1) A Project Manager (Hand 1998) gives access to support databases, a simulation engine, performance assessment tools and 3rd party applications for CAD, visualisation, report synthesis *etc*. Its function is to co-ordinate problem definition and pass the data model between the supporting applications.
b1) Project's commence by making ready the system databases. These include hygro-thermal, embodied energy and optical properties for constructions, typical occupancy profiles, pressure coefficient sets for use with air flow modelling, plant components for use in HVAC modelling, mould species data for use with predicted surface conditions to assess mould growth risk, and climate collections representing different locations and weather severity.
c1) Embedded within such databases is knowledge that supports the design conceptualisation process. For example, the construction elements database contains sets of hygro-thermal and optical properties for a range of construction materials, and derived properties from which behaviour may be deduced (e.g. thermal diffusivity to characterise a construction's rate of response or thermal transmittance to characterise its rate of heat loss).
d1) Although the procedure for problem definition is a matter of personal preference, it is common to commence with the specification of a building's geometry using an external CAD tool or in-built equivalent. ESP-r can inter-operate with dxf compatible programs (e.g. MicroGDS; Morbitzer 2002) that can be used to create models of arbitrary complexity for import to the Project Manager where the attribution process is enabled.
e1) Simple wire-line or false coloured images can be generated as an aid to the communication of design intent or the study of solar/daylight access. The Project Manager provides wire-line photomontages (Parkins 1977) and coloured, textured images via the *Radiance* system (Larson and Shakespeare 1998), automatically generating the required input models, driving *Radiance* and receiving back its outputs.
a2) Constructional and operational attribution is achieved by selecting products (e.g. wall constructions) and entities (e.g. occupancy profiles) from the support databases and associating these with the problem geometry. It is at this stage that the simulation novice will appreciate the importance of a well-conceived problem abstraction that achieves adequate resolution while minimising the number of entities requiring attribution, simulation processing and performance appraisal.
b2) Temperature, wind, radiation and luminance boundary conditions, of the required severity, are now associated with the model. This enables an appraisal of environmental performance (e.g. thermal and visual comfort levels) in order to gain an insight into the extent of any required remedial action. As appropriate, the boundary conditions can be modified to represent extreme weather events or local climate phenomena.
c2) As required, geometrical, constructional or operational changes can be applied to the model in order to determine the impact on performance. For example, alternative constructional systems might be investigated, different occupancy levels imposed, or different approaches to daylight utilisation assessed along with the extent and location of glare as shown in the figure for the case of an office with added light shelf.
d2) Special façade systems might be considered: photovoltaic (PV) components to transform part of the solar power spectrum into electricity (and heat); transparent insulation to passively capture solar energy; or electro-, photo- or thermo-chromic glazings to control glare and/or solar gain. In each case, the contribution to improved performance and reduced energy use can be determined.
e2) To access the energy displacement potential of daylight, a luminaire control system might be introduced, comprising photocells linked to a circuit switch or dimming device. Simulations can then be undertaken to optimise the parameters of this control system in order to minimise the use of electricity for lighting purposes.
a3) The issue of integrated environmental control can now be explored by defining control systems to dictate the availability of heating, cooling, ventilation, lighting *etc*; or to act to resolve conflict between these delivery systems.
b3) To study the feasibility of building ventilation, a flow network can be associated with the building model so that the dynamic interactions are explicitly represented. The control definition may then be extended to apply to the components of this network, e.g. to emulate window opening or flow damper control.
c3) Where mechanical intervention is necessary, a component network can be defined to represent the HVAC system for association with both the building model and any active flow network. The control definition previously established may be further extended to provide internal component control and link the room states to the supply condition.
d3) To examine indoor air quality, spaces within the building model can be further discretised to enable the application of computational fluid dynamics (CFD) in order to evaluate the intra-space air movement and the distribution of temperature, humidity and contaminants such as CO.
e3) While the components of a model, the building, flow and HVAC networks, and the CFD domain, may be processed independently, it is usual to subject them to an integrated assessment whereby the interactions are included. In the example shown here, a house model has been assigned a natural ventilation flow network, a

ventilation heat recovery plant network, a CFD domain to enable an analysis of air quality, and a moisture flow model to allow an assessment of humidity distribution.

a4) A further network might now be added to represent the building's electrical power circuits. This can be used in conjunction with the previously established models for façade-integrated PV, luminaire control, HVAC and flow networks to study scenarios for the local utilisation of the outputs from building-integrated RE components or the shedding of load as an energy efficiency measure. Other technologies, such as □CHP and fuel cells, can also be assessed.

b4) For specialist applications, the resolution of parts of the model can be enhanced to allow the detailed study of particular issues. For example, a portion of a multi-layered wall might be finely discretised to enable the identification of thermal bridges, or a moisture flow network might be added to support an assessment of condensation risk.

c4) By associating the time series pairs of near-surface temperature and relative humidity (to emerge from the integrated building, CFD and network air/moisture flow models) with the growth limit data as held in the mould species database, it is possible to determine the risk of mould growth. Remedial actions may then be explored.

d4) The core message is that any problem, from a single space with simple control and prescribed ventilation, to an entire building with systems, distributed control and enhanced resolutions, can be passed to the Simulator where its multi-variate performance is assessed and made available to inform the process of design evolution. By integrating the different technical domains, the approach supports the identification of trade-offs.

e4) Integrated modelling supports team working because it provides a mechanism whereby the different professional viewpoints can come together and contribute equally to the eventual outcome. Such an inter-disciplinary approach is likely to give rise to more innovative and sustainable solutions.

To further support inter-disciplinary working, it is possible to collate the different aspects of performance and to present these in the form of an Integrated Performance View (IPV). As shown in Figure 5, an IPV might typically cover issues such as seasonal fuel use, gaseous emissions, thermal/visual comfort, daylight utilisation, RE contribution *etc*.

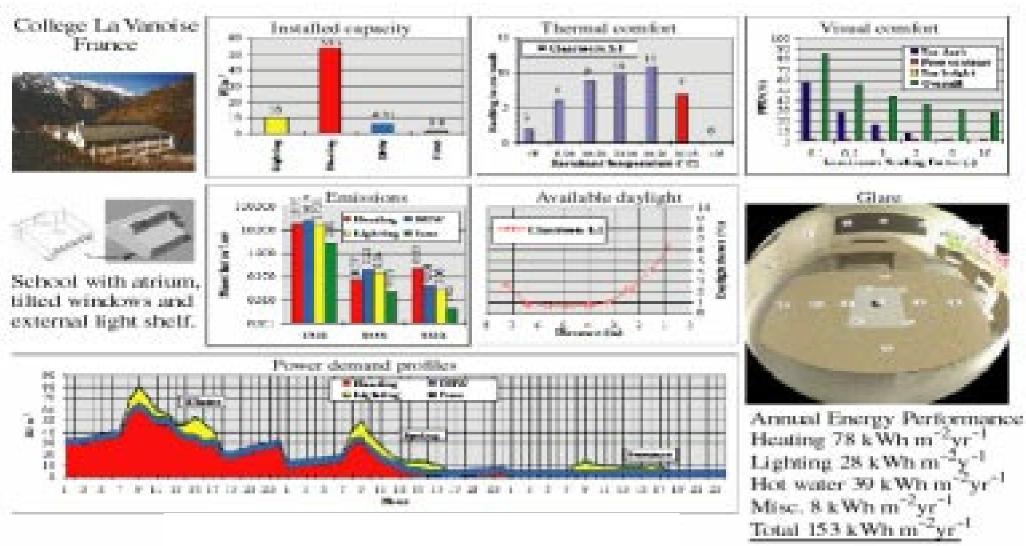

Figure 5: Multi-variate performance summaries support team working.

Citherlet (2001) has extended the integrated performance modelling approach by adding a life cycle impact assessment (LCIA) procedure. This supports the assessment of the energy use and environmental emissions corresponding to the manufacture, transport, assembly, maintenance and disposal of construction materials, in addition to those associated with building environmental control. Four environmental impact indicators are used to quantify the overall impact: global warming potential, acidification potential, ozone generation potential and the use of non-renewable energy. Such impacts may be estimated from the predicted energy demand given that suitable conversion factors are available. At the present time a significant number of modelling systems exist that may be used to address, in whole or part, the performance issues presented above. Details on these systems are available elsewhere (DOE 2002).

INTERNET ENERGY SERVICES

The Internet is now attaining a level of resilience and capacity that will enable it to support a wide range of beneficial information services. The challenge is to develop products that represent a value proposition to citizens and to establish new service providers to deliver these products. Insofar as these challenges can be met, services can be tailored to assist the process of good governance by providing real-time data to decision-makers on issues relating to sustainability. Examples include:

- fuel use by time, type and sector in support of energy efficiency and RE systems deployments;
- emissions monitoring in support of air quality and climate change targets attainment; and
- city performance profiling in support of energy/environment action planning.

Complementary services may also be established to provide direct links to citizens and to support their greater participation in sustainability issues. Examples include:

- home conditions monitoring (e.g. CO and temperature) in support of responsive care provision for vulnerable members of society;
- large scale, synchronised home appliance control in support of electricity base load management; and
- the provision of personalised energy use data to encourage desirable changes in usage patterns.

In addition to the benefits to the service recipients, it is likely that new employment opportunities will arise, both in terms of the jobs associated with service provision and the establishment of new market opportunities for the telecommunications industry. Furthermore, the approach provides an efficient mechanism to implement (low cost) energy systems monitoring in order to track the effectiveness of actions taken in response to future legislation (such as the new European Directive on Building Energy Performance). An Internet service reaches many residences and organisations simultaneously so that decisions relate to the large, aggregate scale. While impacts at the home scale will be of interest to the occupant, the impacts at the large scale will be of interest to local authorities, utilities and government. There are many stakeholders involved in the chain of service delivery including home owners/occupiers and related organisations, property owners/managers/operators, energy suppliers/distributors, local/national authorities, service providers and telecommunications operators.

As an example, the EC funded *SmartHomes* Project (Clarke *et al* 2002) set out to develop and test, by real-scale field trial, a range of new energy/environment services. The aim was to demonstrate that homes could be adapted to acquire and transfer high frequency fuel, power, appliance operation and space temperature data in support of new services of benefit to home owners/occupiers, utilities and local authorities. Examples include:

- environmental monitoring, e.g. detection of gas, smoke, temperature and humidity;
- smart metering, e.g. of gas, electricity and water consumption;
- appliance control, e.g. for heating, lighting and small power;
- weather related services, e.g. heating control, night cooling, use of rain water *etc*;
- performance evaluation, e.g. of city energy consumption by fuel type;
- remote switching of appliances, e.g. for load manipulation and HVAC control; and
- renewable energy trading, e.g. as a function of electricity prices and demand.

The expectation was that substantial energy savings could be achieved by increasing the energy awareness of home owners/occupiers by providing them with statistics on their energy use in relation to that of others in similar circumstances.Within the system, sets of related sensors and actuators exist to support the needs of particular energy services. A communications gateway device, or 'ebox', is employed to receive/send information from/to the sensors/actuators and send/receive data to/from an e-service centre located elsewhere on the Internet. All data are held within a central server database, with software agents acting to extract the aspect data-set corresponding to the particular energy services being supported at any time. Such a data set is either aggregate data, for onward transmission to an energy service provider (ESP), or actuation requests from an ESP for transmission back to homes (via embedded actuation devices). Typically, an ESP will add value by interpreting the data and providing the actual energy/environment service (e.g. by raising an alarm, instigating a home control action or by updating a secondary Web site). For example, information comprising home temperatures and CO levels would permit an ESP to provide a progressive care for the elderly service. Alternatively, information comprising fuel and power usage data would support two ESPs, one concerned with local action planning and the other with the routine dissemination of personalised consumption information to citizens. Figure 6 shows an example of a Web site corresponding to the delivery of personalised fuel use, environmental conditions and cost information to home owners/occupiers.

CONCLUSIONS

This paper has summarised the possibilities for the application of modelling and simulation tools in support of the rational use of energy within the built environment. These applications range from the routine monitoring of fuel use and emissions, through formal methods for selecting suitable means of energy supply, to detailed simulations to tests the robustness of particular schemes. Finally, some possibilities for Internet-enabled energy services were identified and one possible delivery scheme outlined.

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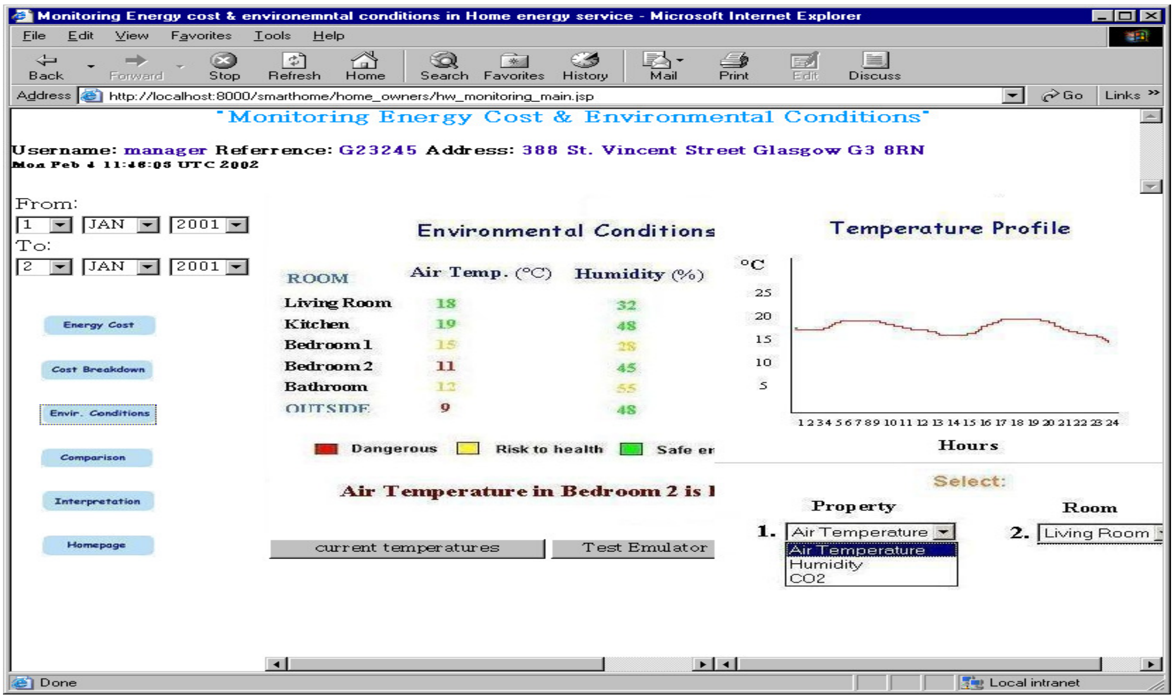

Figure 6: *SmartHomes* Web site for home owners/occupiers.

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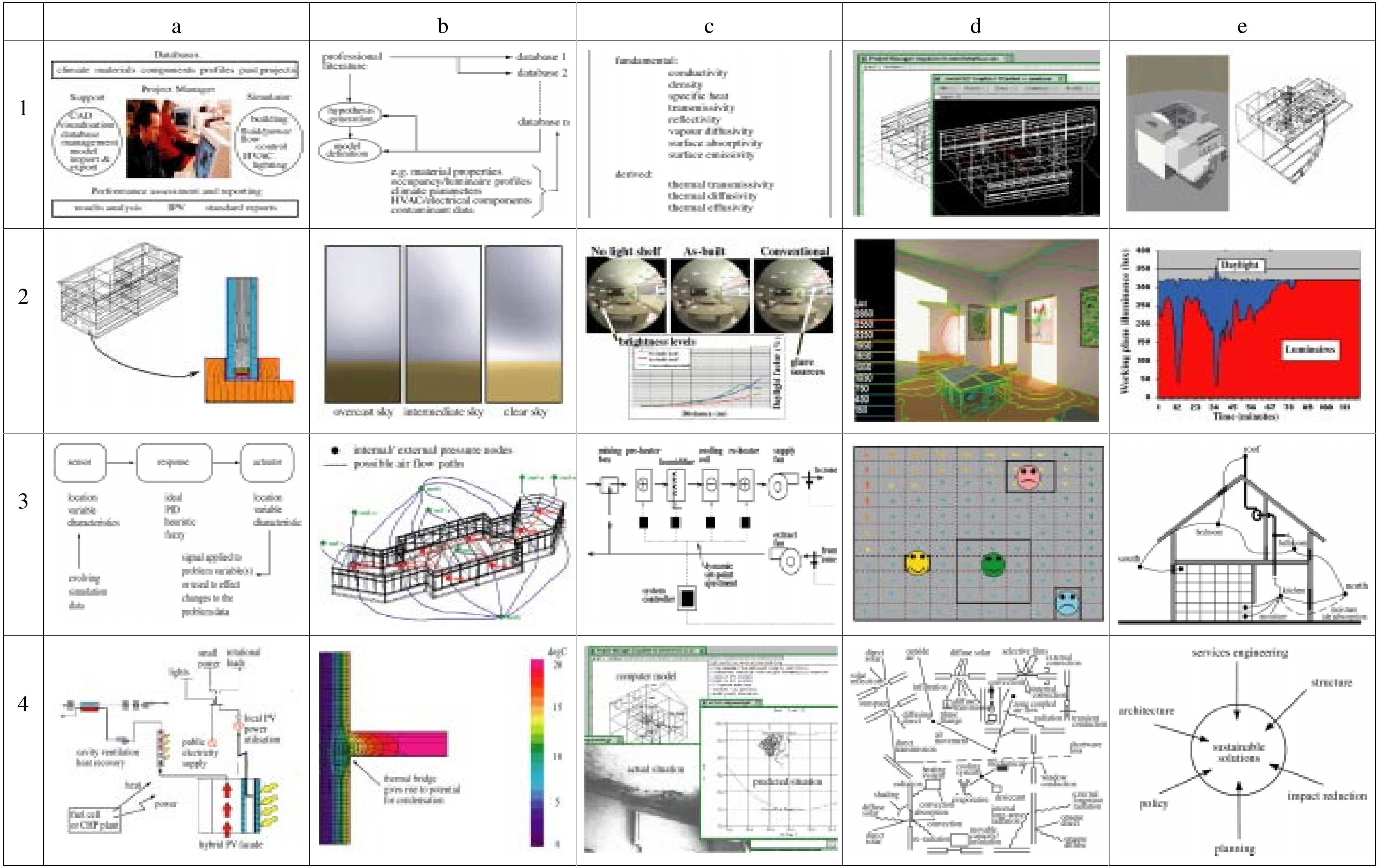

Figure 4: An example of a computational approach to design.