Proceedings of ICAD2009
The Fifth International Conference on Axiomatic Design
Campus de Caparica – March 25-27, 2009
ICAD-2009-29

AN ENERGY EFFICIENCY FRAMEWORK FOR THE DESIGN OF HVAC SYSTEMS

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ABSTRACT

The higher-level functions of heat, ventilation and air-conditioning (HVAC) systems changed along the last forty years, simply from providing thermal comfort to a multipart set of requirements. Since the eighties, HVAC systems must also be able to provide indoor air quality and to recover energy. During the mentioned period, the manufacturing project teams somewhat redesigned those systems in order to accommodate the new FRs. This procedure disagrees with the fifth theorem of Axiomatic Design (AD), which in such cases requires a complete system redesign.

The recent rise in the price of the oil barrel emphasizes the need to recover energy in any building, namely in HVAC systems. The energy regulations, ASHRAE 90.1 in the US and the EPBD (Energy Performance Building Directive) in the EU, address this problem.

The aim of this paper is to analyse an HVAC system that is independent in terms of thermal comfort and indoor air quality, and to add the "reduce energy" functional requirement (FR). This new FR has four "children" functions: "adapt flows", "recover energy", "choose equipment efficiency" and "define efficient network conditions".

Raising the design matrix to a set of well-known market solutions allows identifying the existing couplings. Taking into account the independent solutions alone, and merging them with the guide solutions established in the regulations, one can conclude that regulations might lead to efficient working conditions.

Keywords: Axiomatic Design, Energy, HVAC Systems

1 INTRODUCTION

Energy consumption in buildings and air conditioning systems is heavily dependent on the investment decisions during the design phase. A design team usually assists the investor by informing him about the available design parameters (DP). If the project is of a speculative nature, the trend will be to reduce investment costs, transferring them to the building's running phase. As energy costs are at least 80% of the operating costs of a building, an incorrect decision during the design phase will have a huge economic impact on the building's operating costs.

Moreover, energy consumption in buildings in Western countries represents 30% to 40% of the consumption of the primary energy resources. Therefore, it is important to address the energy consumption in buildings through codes or regulations. Regulations create constraints and define ranges of variation in design parameters or in design functions, which cause the building's energy consumption to conform to acceptable ranges.

In Western countries, it is urgent to reduce fossil fuels consumption due to economic reasons, and to reduce the dependency of imported oil, which is a geo-strategic issue. Furthermore, these countries are committed to reducing greenhouse gases emissions. In addition, there are social costs determined by environmental problems that are caused by fossil fuel consumption. Finally, the recent rise in oil price to 151 USD in July 2008 reminded countries of the importance of taking measures against the shortage of energy resources.

The solution for this shortage imposes that society should modify the current development model so that it becomes based on sustainable systems. It is particularly necessary to consider erecting sustainable buildings, with low energy consumption. One believes that increasing energy efficiency in facilities will help reducing energy consumption. Therefore, it is necessary to evaluate models for reducing energy consumption in buildings, especially in those that are large consumers of energy. These buildings usually have air-conditioning systems.

The aim of this paper is to analyze two functions, namely to "reduce energy consumption in a building that is large consumer of energy" and to "reduce energy consumption in the HVAC system".

Standards, directives and regulations will be used in this paper, to identify the best practices for project facilities. The mapping diagram of the decomposition of those functions will structure the knowledge, resulting in a general framework on how to reduce energy consumption in buildings with HVAC systems. The economic concern with energy consumption, availability of energy resources and global environmental problems, led to regulations on energy consumption in buildings: the "Energy Performance Building Directive" (EPBD) in Europe and the ASHRAE 90 in the United States.

The framework proposed in this paper may support the creation or amendment of legislation, to set codes or to create a methodology that improves the HVAC design process.

2 THE ASHRAE 90.1 STANDARD

In Europe and in the U.S. there are concerns about high-energy consumption in buildings. In the U.S., ASHRAE launched in 1975 its first standard on this issue, which has undergone several revisions over the last decades. Currently, the ASHRAE 90.1 [1], Version 2007, is in force for non-residential and non-industrial buildings.

This standard uses a compulsory language, although it is not a regulation. However, other countries used it as a basis for the establishment of their own regulations.

The scope of ASHRAE 90.1 is the study of the building's envelope, air-conditioning, hot water, lighting and power systems. An entire HVAC design may comply with the standard by three ways: by using pre-set items (the so called simplified method); by the prescriptive method; or by economic evaluation. If the prescription or the economic methods are chosen, the design must fulfil a set of mandatory provisions.

The simplified method applies to single-zone air conditioning systems, whenever the systems serve spaces with areas less than 2,300 m^2. It imposes some features, specifically: a minimum efficiency value for the refrigeration cycle and for the boilers, economizer systems and insulation of ducts and pipes, and heat recovery systems when the outdoor air rate is above 5,000 m^3/h. Moreover, the afore-mentioned simplified method, establish a zone thermostatic control and the central control must not allow simultaneous cycles of cooling and heating. In addition the dampers will close when the equipment stops. Motors exceeding 0.5 kW and cooling and heating equipment exceeding 4.5 kW should stop when not required. At last, the control system should use start up algorithms.

The prescriptive and the economic evaluation methods apply to variable air volume (VAV) systems or other multi zone systems. In such cases, the systems must meet a set of mandatory provisions. The mandatory requirements for these methods include calculating thermal loads according to the ASHRAE. It also defines criteria for duct networks construction and duct tightness requirements. In addition, the mandatory method includes minimum equipment efficiencies on standard and non standard conditions, and the verification of equipment. The prescriptive method allows moisture control through sequence processes of cooling and heating, also allowing the control of ventilation in zones of high occupancy, thus fulfilling the ASHRAE 62.1 requirements. For designs complying with the mandatory provisions, the standard provides prescriptive solutions. These solutions include control systems for air handling units (AHU) with economizers and heat exchangers. It also includes requirements for maximum head loss in the HVAC components and maximum specific fan power (SFP). The standard also prescribes topologies for hydronic networks. It establishes restrictions in the use of high-power pumps, recommend appropriate technologies for heat rejection systems and for heat recovery in chillers and heat pumps. Prescriptions of water economizers are subjected to limitations on pressure drop.

Alternatively, one can use the economic method, as long as the design fulfils the mandatory requirements. This evaluation path uses an energy model for the building, so that ASHRAE 90.1 encourages the use of dynamic multi-zone models. This is why the ASHRAE 2004 version includes the informative Appendix G, concerning the method for classifying the energy performance of buildings.

3 THE EU 91/2002 DIRECTIVE

The main objective of Directive 2002/91 (EPBD) [2] is to increase the energy efficiency in buildings, as a means to reduce energy consumption and to help complying with the Kyoto Protocol.

In 2002, the residential and tertiary sector of the EU-15 absorbed more than 40% of their total energy consumption, and this share has a steady tendency to grow.

The EPBD directive intends to improve the energy management in each country, allowing each EU member state to establish the necessary provisions. These provisions will take into consideration local weather conditions, comfort conditions and the ventilation of spaces. The directive lays down the following requirements:

> "(a) the general framework for a methodology of calculation of the integrated energy performance of buildings;
> (b) the application of minimum requirements on the energy performance of new buildings;
> (c) the application of minimum requirements on the energy performance of large existing buildings that are subject to major renovation;
> (d) energy certification of buildings; and
> (e) regular inspection of boilers and of air-conditioning systems in buildings and in addition an assessment of the heating installation in which the boilers are more than 15 years old".

Although EPDB intends to reduce the energy consumption of buildings, according to the article 4 of the EPBD the adopted requirements should "take account of general indoor climate conditions, in order to avoid possible negative effects such as inadequate ventilation". The directive's preamble also states that the improvement of "the energy performance of buildings should take into account climatic and local conditions as well as indoor climate environment and cost-effectiveness".

The EPBD certification procedure considers the energy consumption after the construction of the building, not taking into account the embodied energy in materials. Thus, it is not difficult to design a building belonging to a good energetic category using new technologies. For low energy consumption, the implementation of these technologies may involve high contents of energy. Examples are the new types of windows, the insulation materials, solar panels for heating or service hot water and photovoltaic panels.

Many components of these technologies will be replaced several times during the lifetime of the building. When applied to single dwellings, the energy for manufacturing these components can equal 25 years of house heating energy [3].

That is, the minimum primary energy consumption of a building that conforms to EPBD does not correspond to the least energy that is required for the life cycle of a building.

The next section presents the EPBD transposition into the legislation of some EU countries, particularly considering the provisions regarding new office buildings.

3.1 THE TRANSPOSITION OF THE EPBD

The legislation of each EU country on the implementation of the EPDB sets limits for the specific annual energy consumption in buildings and the minimum thermal characteristics of their envelope [4]. The legislation of most member states associates energy consumption with the need for indoor thermal comfort and ventilation.

The French legislation sets requirements for the calculation of energy consumption in buildings and the minimum conditions that the systems should meet. Specifically establish that at reference conditions for the HVAC systems, the EER in cooling should be above 2.45. Constant flow pumps and clock systems for starting and stopping the system are prescribed for the calculation as well.

Additionally establishes the maximum influence area for the control system, when applied to systems such as VAV, chilled ceilings or fan-coil units. Any zone with a cooling system should have a ventilation system. Air-conditioning of areas exceeding 400m^2 should include energy consumption meters and areas above 1,000 m^2 should include the measurement of lighting energy.

The Spanish legislation, known as RITE [5], establishes a detailed set of technical requirements that should support the design of the energy facilities for the building. This set of requirements follows the ISO 7730, CR 1752 and EN 13779. A document with a detailed set of possible prescriptions accompanies the legislation [6]. This document is grouped in chapters concerning hygiene and comfort, energy efficiency and safety. Conditions of comfort, indoor air quality, quality of acoustic environment and sufficient allocation of service hot water, must be considered in areas with human occupation. This law particularly requires that boilers should have a minimum of efficiency and that the power equipment should have power steps. It also establishes a minimum insulation level for pipes and ducts and leakage level for air ducts. The components should have maximum head losses, the fan speed should have a control system, the networks should be balanced and the electric motors should have a minimum performance. Additionally humidity control, indoor air quality control and consumption should be measured. The energy consumption due to the Joule effect should be limited. Systems for providing free cooling with outside air, heat recovery from the extract air and the use of renewable energy should be considered. The heat exchangers head loss is limited and minimum values for recovery efficiency are specified for different values of the air flow.

The transposition of European directives into Italian law [7] is a framework document with various attachments. Implementation is phased over the time from 2006 to 2010. The framework specifies a general methodology that provides high freedom in the design process, although it must meet some energy efficiency specifications. These specifications establish the maximum energy consumption of the building, also setting values for heat transfer coefficients for the building's envelope and for the energy efficiency of boilers. The Italian law also requires the presentation of a report on the building containing data concerning the thermal power plant, power generation, system control and energy measurement. Moreover, this report must contains the characterization of the thermal envelope, ventilation rate, systems' efficiency at partial loads, needs of primary energy during the cooling and heating periods and a description of the used renewable energy systems.

The building regulations in Great Britain have separate sections for residential and non-residential buildings, clearly separating existing buildings from new construction. The present paper concerns to the L2A regulation section [8] for new non-residential buildings, which lays on a limit value for CO_2 emissions ("Target CO_2 Emission Rate, or TER). L2A regulation sets limits for the thermal conductivity of the building's envelope and for the air permeability. L2A also defines conditions for the efficacy of lighting systems, and the light switching system should avoid unnecessary lighting, depending on the available daylight. Each zone of the building should have a monitoring system to enable the HVAC system to adapt at its heat loading. In addition, L2A establishes that the control of the energy production system should adjust the loading of heat pumps and boilers. Furthermore, any group of apparatuses that is responsible for more than 90% of the annual energy consumption of each fuel must have meters. For buildings with a floor area exceeding 1,000 m^2, the regulation lays on that they should have monitoring systems. Additionally, L2A sets up minimum values for the efficiency of boilers, both for the nominal conditions and for the seasonal averages. Moreover, L2A defines minimums values for efficiency (EER) and for seasonal efficiency (ESEER) related to heat pumps and other machines with refrigeration cycles. The legislation also establishes a specific amount of energy consumed by unit of airflow (SFP), for each type of application of air distribution systems, and sets limits to the SFP at partial load. In addition, fan motors exceeding 1.1 kW should have variable speed drives. Finally, the regulation stipulates insulation levels for pipes and ducts and vessels.

In Portugal, a framework document called "National System of Certification of Energy and Indoor Air Quality in Buildings" implemented the Directive. This framework document is supported by regulations about the thermal characteristics of buildings (RCCTE) and about the energy systems of climatization (RSECE) [9]. RSECE establishes prescriptions in order to reduce the energy consumption of large buildings other than dwellings. The large building concept applies to those buildings with an area exceeding 1,000 m^2 or with cooling systems exceeding 25 kW. The Portuguese regulation sets limits to the nominal consumption, which is given by the energy efficiency indicator (IEE). The IEE defines the energy classification of the buildings. To obtain the IEE indicator, one should model a building similar to the real one, which is subjected to pre-defined nominal loads and schedules. The RSECE establishes specifications for the indoor air quality based on the outdoor air ventilation rate. This ventilation rate is calculated according to the human occupation or the served floor area. In addition, RSECE requires a centralized system for the production of heat and cold, which power limits, should fit the computed heat load. Furthermore, the regulation requires the use of renewable energy and, in certain cases, the use of a cogeneration system. The RSECE regulation also compels the use of energy recovery systems in heating mode for systems which exhaust air contains a thermal load exceeding 80 kW. In addition systems having (air handling unit) AHUs with a total airflow rate supply greater than 10,000 m^3/h should have free-cooling devices. The regulation also provisions for boilers and establishes power steps for the heating equipment. Moreover, this regulation limits the Joule effect heating to a maximum of 5% of the heating load. Pipes and tubes should have minimum thickness insulation. In what concerns to the control system, RSECE establishes that the design should define the temperature control system, the time switch control and the step control system for the power equipment in heating or cooling mode. Finally, the regulation defines individual meters of energy for power equipment exceeding 12 kW, or for thermal power equipment above 100 kW.

4 ENERGY IN BUILDINGS – FUNCTIONAL REQUIREMENTS AND DESIGN PARAMETERS

Reducing the energy consumption of an HVAC system highly depends on the characteristics of the building where the system is installed. The decrease on the energy consumption firstly depends on the possibility of reducing the building internal loads. Energy consumption also depends on the urban design and climate. Nevertheless, the urban design and climate is not in the scope of this paper. Instead, this paper will address a building project with floors, areas, facades, glazing spans and all other architectural elements. One considers the building as an office building, or one of a similar kind, with high internal loads.

The conclusions of this paper may be used to design an air conditioning system, to lead reforming an energy design code or to reformulate regulations on energy in buildings.

In order to define the functions and design parameters, one uses the guidelines of the legislation and regulations that are described in section 3. The only goal of using these documents is to validate our selection of design requirements and parameters. One does not intend to provide a comparison between the various EPBD implementations. Moreover, the documentation of each country that we have used is not exhaustive. Actually, some EPBD implementation calls for other national laws or for regulations.

4.1 MAPPING OF REDUCING ENERGY CONSUMPTION IN BUILDINGS

The thermal load calculation of a building accounts for the loads of human occupancy, electric equipment, lighting devices and outdoor air. This calculation also considers the exchanges of heat throughout the building envelope. The solar radiation through the glass spans and the conduction through walls, floors and roofs are the main modes of heat transfer through the building envelope. The thermal load calculation also takes in account the loads induced by the operation of electric motors and by other power systems.

The functions belonging to the first level of the decomposition process should hold together the goal of reducing energy consumption in buildings: “adjust building inertia”, “adjust building envelope”, “reduce the internal loads”, “reduce the consumption of energy systems” and “produce locally energy efficiently” (more efficiently than the one available in urban networks).

Figure 1 depicts the mapping of the above-mentioned functions. Eq. (1) shows the design matrix (DM) with the relationships between functional requirements and design parameters. For ease of reading, full lines split levels of decomposition and slashed lines divide the corresponding sub-levels of Eq. (1).

The lower level parameters of this decomposition are DP2.1, mass per unit area of typical materials that stores energy; DP2.2, heat transfer coefficient of the building envelope, whose variation increases or reduces the heat-flow through walls; DP2.3, product of the area of glazing by the glazing and shading factors, which can be adjusted to achieve certain solar gain; DP2.4, number of persons, usually a pre-defined parameter; DP2.5, interior equipments, which includes all the equipment in office environments, except luminaries; DP2.6, the efficiency of the lighting system that might be tuned considering the effects of solar radiation; DP2.7, appropriate outdoor air flow, particularly dependent on the number of persons; DP2.8, DP2.9 and DP2.10, related to the choice of the overall efficiency of power systems, service hot water systems and HVAC systems; and finally DP2.11 to DP2.13, related to the own production of energy.

Eq. (1) makes clear that setting the building envelope plays an important role in reducing energy consumption. This relation states that FR1.2 depends on FR1.3, i.e. the characteristics of the building envelope should be adjusted after knowing the internal load. The main conclusion from this relationship is the need of tuning the heat transfer coefficient of the building wall after calculating the load inside the building, which in turn will affect the internal load of the building. The lines of functional requirements FR1.3 and FR2.2 highlight this coupling.

However, in common designs, the internal loads do not interfere in the definition of the heat transfer coefficient, which is usually defined by standard values. Anyway, it may be difficult to determine the building envelope characteristics, given the uncertainty of the building occupation, use and evolution during its life cycle.

There is a relationship between solar gain and lighting load, as the solar radiation through the glazing area helps reducing the lighting needs.

Therefore, this mutual dependency couples the glazing span and the active lighting system characteristics. The lines of functional requirements FR2.3 and FR2.6 highlight this feature. Moreover, the absorption of the solar radiation depends on the inertia of the building. Finally, the outdoor airflow rate depends on the number of persons. The indoor air quality increases with the outdoor air rate, and this usually helps removing a fraction of the internal load.

The use of “o” in Eq. (1) denotes the impossibility of changing the number of persons in the design process. Finally, setting the service hot water system depends on using the rejected heat from the HVAC or cogeneration systems, or the heat available from renewable energy systems. These relations express that the decisions on the HVAC or on the service hot water systems, should be made after looking for producing energy locally.

Usually, one sets up the lighting system, the insulation of the building envelope and the outdoors air rate without noticing the couplings expressed in the design matrix. A regulation concerning the glassing area would be welcome to help removing the FR2.3-FR2.6 coupling.

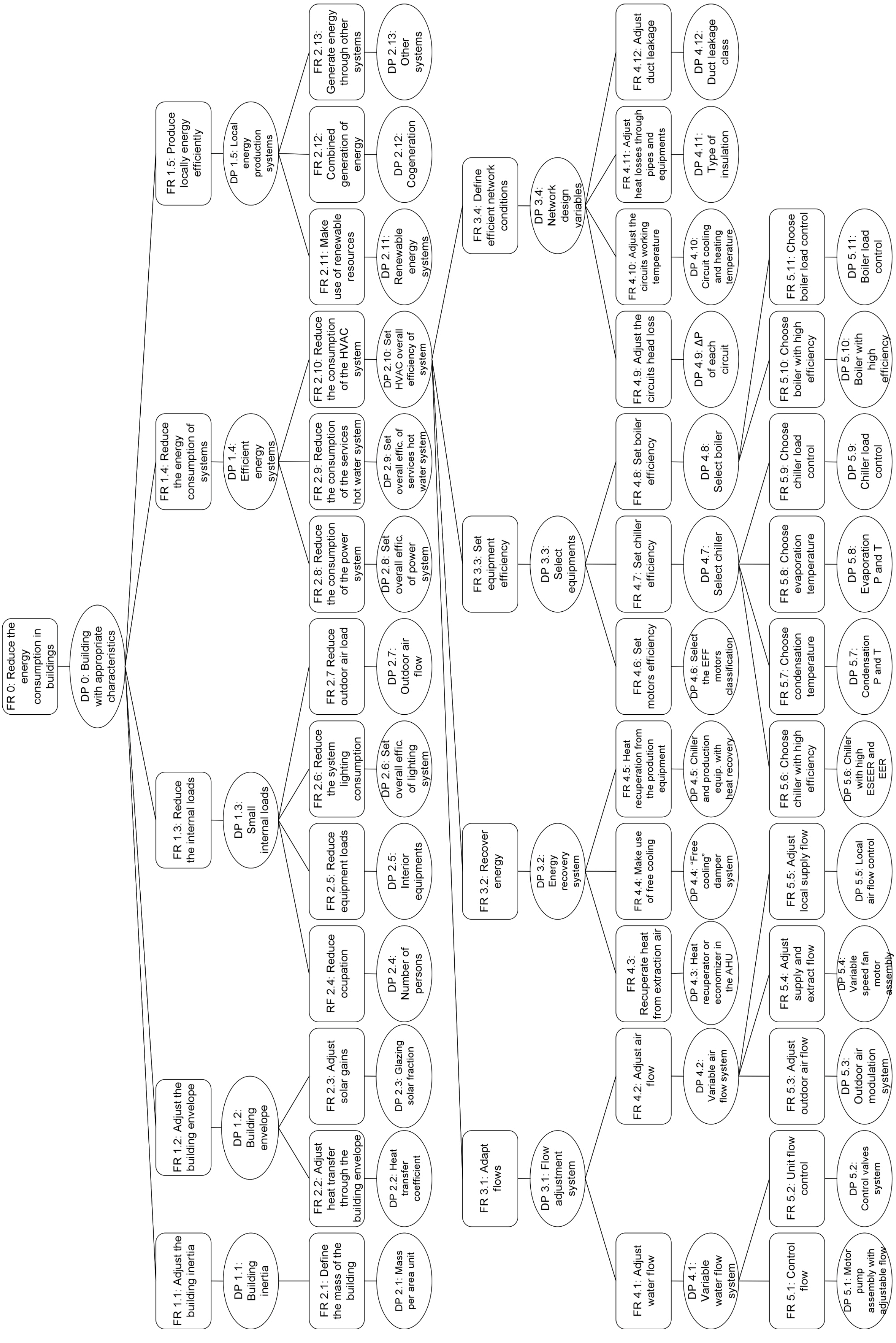

Figure 1. The mapping process for FR0 (Reduce the energy consumption in buildings)

Next, one defines the glazing and the minimum outdoor airflow. The system seems decoupled, although the resulting design is probably not the best in terms of energy performance of the building.

$$\begin{bmatrix} FR0 \\ FR1.1 \\ FR1.2 \\ FR1.3 \\ FR1.4 \\ FR1.5 \\ FR2.1 \\ FR2.2 \\ FR2.3 \\ FR2.4 \\ FR2.5 \\ FR2.6 \\ FR2.7 \\ FR2.8 \\ FR2.9 \\ FR2.10 \\ FR2.11 \\ FR2.12 \\ FR2.13 \end{bmatrix} = \begin{bmatrix} X & & & & & & & & & & & & & & & & & & \\ & X & & & & & & & & & & & & & & & & & \\ & & X & X & & & & & & & & & & & & & & & \\ & & & X & & & & X & & & & & & & & & & & \\ & & & & X & X & & & & & & & & & & & & & \\ & & & & & X & & & & & & & & & & & & & \\ & & & & & & X & & & & & & & & & & & & \\ & & & X & & & & X & & & & & & & & & & & \\ & & & & & & x & & X & & & X & & & & & & & \\ & & & & & & & & & X & & & & & & & & & \\ & & & & & & & & & & X & & & & & & & & \\ & & & & & & & & X & & & X & & & & & & & \\ & & & & & & & & & o & & & X & & & & & & \\ & & & & & & & & & & & & & X & & & & & \\ & & & & & & & & & & & & & & X & X & X & X & \\ & & & & & & & & & & & & & & & X & x & & \\ & & & & & & & & & & & & & & & & X & & \\ & & & & & & & & & & & & & & & & & X & \\ & & & & & & & & & & & & & & & & & & X \end{bmatrix} * \begin{bmatrix} DP0 \\ DP1.1 \\ DP1.2 \\ DP1.3 \\ DP1.4 \\ DP1.5 \\ DP2.1 \\ DP2.2 \\ DP2.3 \\ DP2.4 \\ DP2.5 \\ DP2.6 \\ DP2.7 \\ DP2.8 \\ DP2.9 \\ DP2.10 \\ DP2.11 \\ DP2.12 \\ DP2.13 \end{bmatrix} \quad (1)$$

4.2 MAPPING OF REDUCING ENERGY CONSUMPTION IN HVAC SYSTEMS

As one can see, the hierarchical decomposition of the global design starts with considerations about the design of the building, which should be clarified at the second level of decomposition process.

From the third level downwards, the design team must deal with the specifics of the different subsystems of the building, of which DP2.10 (Reduce the consumption of the HVAC systems) is the focus of this work.

In order to reduce the consumption of the HVAC system, one might pay attention to the following details:

- A control system should adjust the water flow by tuning the speed of motor pump groups of variable flow, depending on the opening of the valve system. A different control system should adjust the air flow, varying the speed of fan-motor groups in the AHU's, according to the locally necessary air-flow rate. Additionally the AHU's should use the correct outdoor air-flow rate in order to provide the necessary indoor air quality level.

- An energy recover system should recover the available heat of the extracted air by the use of heat exchangers or economizers in the AHU's. Furthermore, the AHU's should be assembled so that they may use directly the outdoor air as a means to cool (free-cooling). Chillers, boilers and other energy production groups should recover the available heat released to the atmosphere.

- The designer should set the equipment efficiency, specifically the rating of the electrical motors (EFF rating), chillers and boilers. The overall efficiency of the chillers depends on nominal and seasonal efficiency (EER and ESEER), evaporation and condensation temperatures, and load control. The evaporation and condensation temperatures should be as close as possible. The boilers' overall efficiency depends on their nominal efficiency and load control.

- Finally, the design should define the appropriate head loss in the water and air networks, according to economical or energetic criteria. These criteria should take in account the head losses of the equipments. The design should also define the appropriate working temperatures for the air and water networks in cooling and heating mode.
In addition, the design should specify a suitable thermal insulation of pipes, ducts and vessels, and the leakage class of the air circuit.

All the fourth level parameters of Figure 1 appear in some of the previously presented regulations, with the exception of DP4.10. Some regulations recommend water and air variable flow systems (DP4.1 and DP4.2), as it is the case of ASHRAE 90.1, and British, Spanish and Portuguese regulations.

The parameters DP4.3 and DP4.4 express one of the purposes of the EPBD directive, therefore occurring in most of the regulations. ASHRAE 90.1 clearly recommends the heat recovery from the production equipment (DP4.5). The minimum performance of equipments, including electrical motors, boilers or chillers, has their values prescribed in various regulations (DP4.6, DP4.7 and DP4.8). ASHRAE 90.1 also establishes general provisions for verification of equipments.

The imposition of limits to energy per unit of flow (SFP), which appears in Great-Britain and Irish regulations as well as in ASHRAE 90.1, indirectly guarantees a head loss (DP4.9) in air circuits. The Spanish regulation also lays limits on the head loss for different components of the air network subsystem. ASHRAE 90.1 sets limitations on the use of high-power pumps, which clarifies the achievement of DP4.9 in what concerns to the water network. In all the other regulations, the head loss in water and air circuits accounts for the total energy consumption of the building.

The temperature in cooling and heating modes (DP4.10) for the air network operation is generally specified by codes, unlike the temperature of hydraulic networks that is seldom defined. Finally, DP4.11 and DP4.12 are mentioned, particularly in the Portuguese, Spanish and Irish implementations of the directive. It also appears in ASHRAE 90.1 standard and in the L2A regulation.

The control system for the above set of parameters appears repeatedly in the legislation of the Great-Britain and in ASHRAE 90.1. In the mapping process of Figure 1, functions and design parameters related to the control system do not appear explicitly. Anyway, they are embedded in some of the functions that include the words "adjust" or "control. The specific functions and parameters of the control system would occur at levels of greater detail.

Some regulations have exclusions, e.g. , for simultaneous heating and cooling or for heating through the Joule effect. These exclusions do not appear in the functional decomposition, because the mapping is performed with design choices, not with the design restrictions. However, it is usual a regulation to have restrictions or checking processes in order to avoid the use of low-cost solutions with high-energy consumption.

The DM shows the important role of the network design variables (DP4.9 and DP4.10). During the early design stages, the project team usually presupposes these design variables, mostly by making use of standard market values. Defining or assuming these design variables makes the design seeming an independent design.

Eq. (2) also highlights that the recovery of heat from the exhaust air (FR4.3) should consider the available head loss (DP4.9). In other words, the use of heat exchangers may have an undesirable effect on the reduction of energy consumption. The definition of a head loss in the heat exchangers allows limiting the handicap condition reported above. This prescription arises in the Spanish legislation. A similar effect happens when using heat recovery in chillers and production equipment with heat recovery (FR4.5), which necessarily involves an increase in head loss and an increase in energy consumption. If the heat exchange systems are in continuous operation and if the payback periods are small, the heat recovery can be counterproductive.

Setting chiller (FR4.7) and boilers (FR4.8) efficiency depends on the temperature of air and water circuits (DP4.10). The higher is the chilled water temperature, the better is the chiller efficiency, but the larger the ducts and pipes will be, and the larger the size of the heat exchangers. A similar consequence occurs if a temperature reduction is specified for the hot water circuit (lines FR5.7 and FR5.8).

$$\begin{bmatrix} FR2.10 \\ FR3.1 \\ FR3.2 \\ FR3.3 \\ FR3.4 \\ FR4.1 \\ FR4.2 \\ FR4.3 \\ FR4.4 \\ FR4.5 \\ FR4.6 \\ FR4.7 \\ FR4.8 \\ FR4.9 \\ FR4.10 \\ FR4.11 \\ FR4.12 \\ FR5.1 \\ FR5.2 \\ FR5.3 \\ FR5.4 \\ FR5.5 \\ FR5.6 \\ FR5.7 \\ FR5.8 \\ FR5.9 \\ FR5.10 \\ FR5.11 \end{bmatrix} = \left[\begin{array}{*{28}{c}}
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Finally, the insulation of ducts, pipes and equipments (FR4.11) slightly depend on DP4.10. The FR4.12, leakage class of the ducts, is also slightly dependent on the loss of pressure in the air circuit (DP4.9).

Reducing the energy consumption by choosing "network design variables" (DP3.4), in order to reduce the energy consumption, usually results in the choice of equipment, pipes or ducts of larger size. The increase in the size of components usually increases the cost and the energy embedded in materials. Consequently, the process design should achieve an optimum size for components. The usual desired solution is the choice of materials that minimize the cost of operation, all over the system's life cycle.

5 CONCLUSION

The different EU countries transposed the Energy Performance Building Directive (EPBD) in their specific regulations. These regulations establish provisions aiming to reduce the energy consumption in buildings. In this paper, the mapping process of the Axiomatic Design (AD) is an attempt to structure provisions, for the top-level requirement of "reducing energy consumption in buildings". The decomposition was undertaken until the second level, except for sub-function "reduce the energy consumption in HVAC systems", which was decomposed until the fifth level.

One may conclude that there are some ontological differences between the objectives of AD and those of a regulation. In fact, AD aims choosing parameters, while regulations often intend to establish restrictions.

As a methodological rule, one indicates that the characteristics of the building envelope might be defined after the characterization of the building use, despite the difficulty in knowing the evolution of its use.

As a minor contribution to future amendments to regulations, one suggests the introduction of boundaries in the use of glazing areas. The definition of the boundaries should take in account the contribution of daylight to achieve the interior lighting requirements.

Moreover, prior to define the HVAC or the service hot water systems, one might check for using local energy production systems.

One may also conclude that the various EU regulations assumed usual network temperatures and head losses, for dimensioning facilities that are not necessarily the most economic values. Finally, one may state that apart from the temperature and pressure drop, all the efficiency related items are independent.

AKNOWLEDGMENT

The authors of this paper would like to thank the Faculty of Science and Technology of The New University of Lisbon, and the Portuguese Foundation for Science and Technology, which valuable support is making possible their research work.

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