Proceedings of ICAD2013
The Seventh International Conference on Axiomatic Design
Worcester – June 27-28, 2013
ICAD-2013-06

DECISION CRITERIA FOR THE DESIGN OF HVAC SYSTEMS FOR DATACOM CENTRES BASED ON COST AND LOSSES DUE TO THE FAILURE OF COMPONENTS

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ABSTRACT

Most of the times, the high-level decision process uses scarce knowledge and data, but has a huge impact over the entire design of an artefact or an organization. This paper is a contribution to help making the best decision, using only the expected ranges of variation of the requirements for each alternative design solution.

As an application, this study focuses on the high-level decision between a chilled water and a direct expansion air conditioning system for a datacom centre. The decision depends on the cost and on the likelihood of failure, assuming that both systems have suitable basic cooling function performance. On the contrary to what is specified in most applications, cost applies herein for a functional requirement with specific ranges of variation. Moreover, one applies Axiomatic Design to the process of decision making, rather than to the definition of the artefact. The collected data helps to define the ranges of variation of the afore-mentioned functions, which are the only records needed for the decision process.

Notice that these ranges are also possible to obtain from a panel of experts in the field. As a result, this approach has a much wider purpose when there is just a global understanding of the phenomenon under discussion.

Keywords: Decision criterion, Information Axiom, fuzzy sets, FMEA, datacom-centre.

1 INTRODUCTION

When choosing between different technical infrastructures the decider needs to know about the features of each solution as well as their costs. Usually, there are some basic functional requirements that all the proposed systems can fulfil, and some characteristics or features that define the quality of the solution. In this context, quality is "the totality of features and characteristics of a product or service that bears its ability to satisfy stated or implied needs", according to the ISO 8402-1986 standard.

On the other hand, cost is a key factor that helps making a decision, which is dependent on the required quality for the investment and on the approach to the contractor market. Usually, entrepreneurs make a public procurement and decide to commission the supplier that proposes the lowest cost. Other entrepreneurs tend to define the limits for the cost in order to be in a safe position regarding the execution of the assignment. It is also common that an investor invites just a set of suppliers, with whom he or she has confidence. Some other investors decide their investments directly with the contractors, because they get the necessary support or have the required self-reliance. What happens in the market exceeds all the afore-mentioned situations, but these examples show that the contractor market has segments, as it happens in any other kind of market. Therefore, the cost is not always a constraint and may have ranges that indirectly relate to expressed or unexpressed features, such as confidence, reliability of work, knowledge, technical support before commissioning and after sales, financial ability, accessibility and friendship, availability to the assignment, etc. In other words, in the context of Axiomatic Design (AD), an empirical function can be used to model the cost. This function is usually based on competition, which final parameter may be the overall cost [Gonçalves-Coelho *et al.*, 2007]. Through the higher levels of decision, the segmentation of the embedded quality of the alternative solutions has a counterpart in different ranges of cost. On the other hand, in lower levels of decision making cost may become a constraint, after the target segment of the market for the system is defined.

For those reasons, the main issues at a high-level decision process are: "to define a technical system"; "to define the quality for the technical system"; and "to define the model for costs". Figure 1 depicts those functional requirements (FR) and the corresponding design parameters (DP).

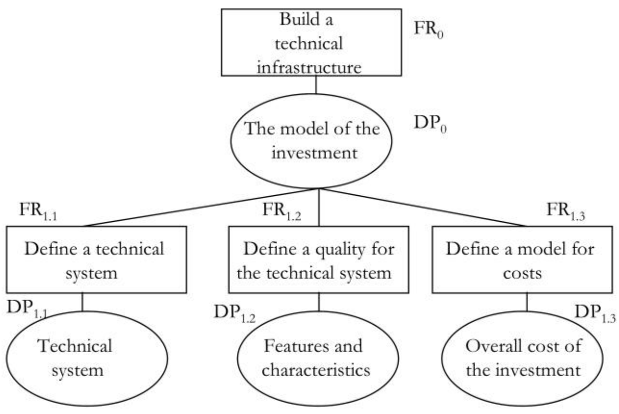

Figure 1. Investment decomposition.

Notice that the technical system may impact the definition of the features and characteristics, and that the overall cost of the investment depends on the chosen FRs. Eq. (1) is the design equation, which expresses the relationships between DPs and FRs, where X denotes a strong relationship and x a weak relationship. Blank spaces are used for inexistent or almost inexistent relationships.

$$\begin{bmatrix} FR_0 \\ FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \end{bmatrix} = \begin{bmatrix} X & & & \\ & X & & \\ & x & X & \\ & X & X & X \end{bmatrix} * \begin{bmatrix} DP_0 \\ DP_{1.1} \\ DP_{1.2} \\ DP_4 \end{bmatrix} \quad (1)$$

Eq. (1) might be read as follows: when choosing a system, there is room to choose the features, and cost can still vary after selecting the system and the features.

2 KEY CONCEPTS OF AXIOMATIC DESIGN

According to AD, the design of a product is a zigzagging decision process between the functional domain and the physical domain. AD stems on two axioms, the Independence Axiom and the Information Axiom. A possible statement for the Independence Axiom is that "in an acceptable design, mapping between FRs and DPs is such that each FR can be satisfied without affecting the other FRs" [Suh, 1990].

From the description of the highest-level functional requirements, one defines the corresponding design parameters, which will have a decisive influence on the designation of the child functional requirements.

During this process, the designer may decide to have more design parameters than functional requirements, making some of the former to be fulfilled by more than one of the latter. This decision may happen for different purposes, but in the context of this paper, the objective of using more design parameters than functional requirements is to achieve a safer system.

2.1 REDUNDANT DESIGNS

When the design has more design parameters than functional requirements, then the design matrix is rectangular and the design is redundant [Suh, 1990]. Eq. (2) shows an example of a redundant design, where both FR_2 and FR_3 depend on DP_3 and DP_4, causing the design to be coupled.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} & X & X & \\ X & X & X & X \\ X & X & X & X \end{bmatrix} * \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{bmatrix} \quad (2)$$

If the design matrix is of the right-trapezoid or rhomboid types, then the design is decoupled [Gonçalves-Coelho *et al.*, 2012].

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} X & X & X & X & \\ & X & X & X & X \end{bmatrix} * \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{bmatrix} \quad (3)$$

The design matrix of Eq. (3) is rhomboid. In order to fulfil all its requirements, the designer may freeze DP_2, DP_3 and DP_4, and achieve FR_1 by adjusting DP_1. After setting DP_1, he or she can achieve FR_2 by adjusting DP_5.

2.2 TOTALLING THE INFORMATION CONTENT

According to the Information Axiom, from the known alternative design solutions, the one chosen might have the minimum information content. One calculates the information in the functional requirement domain by defining a system probability distribution function (p.d.f.) that expresses the behaviour of the system.

Eq. (4) allows computing the information content I for a one-FR design, where P is the probability for the system to perform within its design range.

$$I = \log_2 \frac{1}{P} = -\log_2 P \quad (4)$$

Usually, the system p.d.f. is either unknown or hard to figure out, but one knows a range of variation and has a limited knowledge of the system performance. In such condition, one can assess the information content by computing the quotient of the common area by the system area defined through a membership function [Kulak *et al.*, 2004] (Figure 2).

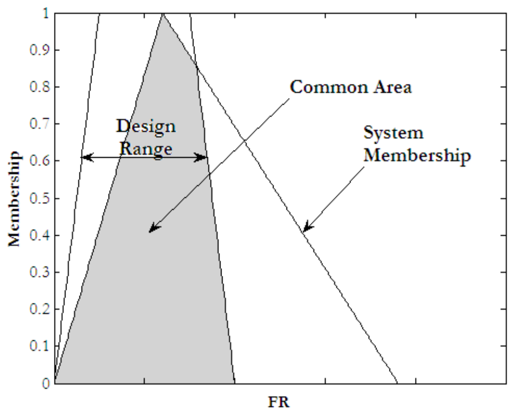

Figure 2. The common area and the system membership.

$$I = -\log_2 \left(\frac{\text{Common area}}{\text{System area}} \right) \quad (5)$$

If the design has more than one FR and is uncoupled, then all FR are achieved independently and the information content of the design is the sum of the information content of each FR:

$$I = -\log_2 (P) = -\log_2 \left(\prod_i P_i \right) = \sum_i I_i \quad (6)$$

The computation of the information content of decoupled designs, such as the one of Eq. (1), involves the use of conditional probability as explained by Frey *et al.* [2000].

3 THE DECISION ON THE HVAC SYSTEM FOR A DATACOM CENTRE

In this section, one applies the above-mentioned summary of AD to help decide which system is the best for a datacom centre. The systems to be compared are a chilled water (CW) cooling system and a direct expansion (DX) one, each of them with redundant and non-redundant variants. The next subsection presents general knowledge about data centres and the following ones describe the FRs to perform, the corresponding DPs, the design matrix for all the four design variants that were considered and the information content.

3.1 The State of the Art in HVAC Systems for Data Centres

Data centres are critical components in the telecommunication and computer industries, as well as in all kinds of businesses. They must run 24/24 all 365 days of the year. Data centres of enterprises have power densities ranging from 500 W/m^2 to 1,000 W/m^2, occasionally going up to 2,000 W/m^2. In the computer industry, the power density may range from 1 kW/m^2 in tape storage data centres, to 60 kW/m^2 in extreme power density applications [ASHRAE Handbook, 2011]. Some years ago, 2,000 W/m^2 was usually considered or the power indicated by the equipment nameplates was used instead. Nowadays, the IT companies tend to give more accurate values for the density to consider, since most of the time the systems might run at 10% of their maximum power. As for datacom equipment, the power per server rack may be as low as 1 kW or as high as 20 kW, and an average power density of 1,500 W per square meter of area of the room housing the equipment is usually assumed [Beaty and Schmidt, 2004].

Internal conditions of temperature and humidity vary widely, depending on the class of the equipment. As a recommendation for all classes, ASHRAE assumes a temperature range of 18 ºC to 27 ºC and a maximum relative humidity (rh) of 60%. However, the relative humidity should be over 30% in order to avoid severe electrostatic discharges.

For low power density data centres (1.2 kW/m^2 to 1.5 kW/m^2), the HVAC architecture is usually based on distributed cooled air. The cooled air comes under a raised floor or instead is ducted close to the ceiling. In these situations, the most usual solutions are the computer room air conditioning (CRAC), in which the cabinets are located inside the room, and the computer air-handling unit (CAHU) with its central air-handling unit (AHU). Both solutions have similar energy consumptions.

One can also use the so-called in row air handlers (IRAH), in which the cabinets are placed in the row of servers that provides cooling. These systems are usually water-cooled.

High-density installations use water to remove the heat directly from ultra-compact blade servers. In addition, the use of dielectric refrigerants is being developed in order to avoid damaging the electronic circuitry in the event of leak [Hughes and Tschudi, 2011].

As for the distribution of cooled air, the hot aisle/cold aisle is the most common arrangement, and the use fan powered cabinets to extract cold air directly from the free space under the raised floor is also usual.

As one could see, datacom centres have high power consumption, making the energy management a special concern in the design of any HVAC system. A typical way to reduce the energy consumption is to manage the IT system by aggregating traffic and using the coalescence of the workloads in smaller groups of servers, in order to allow disconnecting the idling systems [Mahadevan *et al.*, 2011]. On the HVAC side, free cooling by using direct air from outside is a potentially interesting technique to remove heat from data-centres [Siriwardana *et al.*, 2013; Cho *et al.*, 2012; Lu *et al.*, 2011] located in frigid, temperate or subtropical regions. Anyway, according to the ASHRAE guidelines about data centres, the air of data centres must follow ISO 14644-1 Class 8 standard, which involves a high filtration requirements of the outside air. Therefore, there should be a special care when using the free-cooling technique due to the likely failures that particles may cause to the system, and failure mode and effect analysis (FMEA) is useful to identify the subsystems or components that are more likely to fail [Dai *et al.*, 2012].

Because the HVAC system might ensure the continuous, faultless running of the IT system, it might have redundancy of the critical components, a condition that is typically achieved by installing two or more components with the same functionality.

3.2 Description of the Application

In this application, the authors used data from twelve datacom centres. Some of those centres are fitted with CRAC units others integrate a CAHU. In all the studied cases, the void of the raised floor ducts the air reaching the cold aisles through vents across the floor. All those datacom centres are situated in a tropical region. Their power density is lower than 1.5 kW/m^2, and they were designed to keep the indoor temperature at 21 ºC. All sites have redundant HVAC systems by inclusion of an extra chiller (to be triggered in the event of failure of the other chiller) and at least two AHU.

This paper addresses the issue of whether to use chilled water units, either CRAC or CAHU, or to use direct expansion CRAC units. Two levels of safety for the system definition are considered: a less safe, non-redundant hypothesis, and a redundant alternative for increased safety. Both safety levels are achieved by employing of-the-shelf HVAC components. Applying each of these levels of safety to CW and DX variants, one obtains the four HVAC specific solutions herein discussed.

3.3 Mapping and the Design Matrix

Figure 3 and Figure 4 allow comparing the higher-level decomposition stages of both non-redundant and redundant HVAC systems. The technical systems and their quality are denoted by the functional requirement "Provide air conditioning to a datacom centre", FR_0., at the top level of the architectures that are depicted in both figures. This FR should be achieved through the design parameter DP_0. At the first level of the zigzag decomposition, both the non-redundant and the redundant systems have the same FRs.

The functional requirement $FR_{1.1}$ of Figure 3 and Figure 4, "define a HVAC system", combines both the $FR_{1.1}$ and

$FR_{1.2}$ of Figure 1 (i.e., the definition of the technical system and its quality). In reality, in the mappings of Figure 3 and Figure 4 it is assumed a quality for the whole systems that meets the quality requirements of a datacom centre.

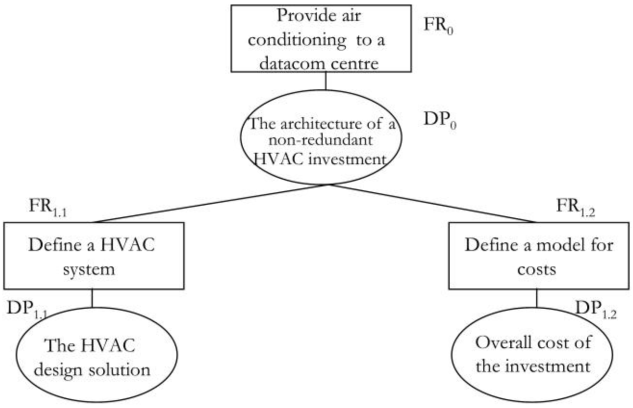

Figure 4. The higher-level decomposition stages of a non-redundant HVAC system.

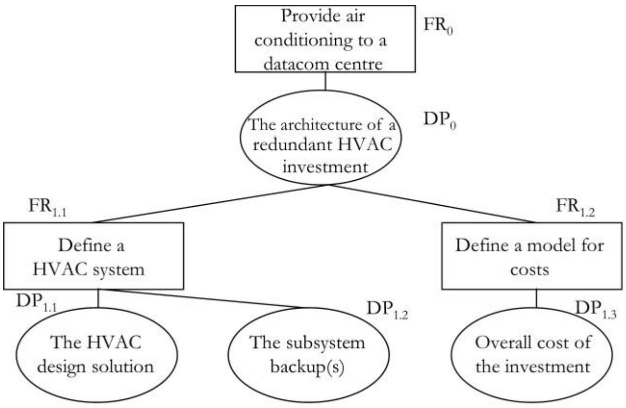

Figure 5. The higher-level decomposition stages of a redundant HVAC system.

As a result, the design equation of the redundant systems necessarily displays more DPs that FRs:

Eq. (7) denotes the design matrix of the non-redundant HVAC systems, from which one can ascertain that they are decoupled designs.

$$\begin{bmatrix} FR_0 \\ FR_{1.1} \\ FR_{1.2} \end{bmatrix} = \begin{bmatrix} X & & \\ & X & \\ & X & X \end{bmatrix} * \begin{bmatrix} DP_0 \\ DP_{1.1} \\ DP_{1.2} \end{bmatrix} \qquad (7)$$

In the redundant design, the decomposition of $FR_{1.1}$ encompasses the HVAC design solution and the subsystem backup(s), $DP_{1.1}$ and $DP_{1.2}$, as shown in Figure 5. Eq. (8) is the design equation of the redundant design solutions.

$$\begin{bmatrix} FR_0 \\ FR_{1.1} \\ FR_{1.2} \end{bmatrix} = \begin{bmatrix} X & & & \\ & X & X & \\ & X & X & X \end{bmatrix} * \begin{bmatrix} DP_0 \\ DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \end{bmatrix} \qquad (8)$$

Since all the four design solutions expressed by Eq. (7) and Eq. (8) are decoupled, one has to use the Information Axiom in order to choose the best one. Classifying the design allows defining the way to compute the information. Notice that the information content of each solution may vary depending on the system architecture, so that it is plausible to find the minimum information content for different design solutions in different ranges of the same FRs.

The computation of the information content for each one of the alternative solutions employed the conditional probability of success for the system failure and for the cost.

The total information content is the sum of the information content of the system performance plus the joint information content of its cost [Frey *et al.*, 2000]. As for the redundant system of Eq. (8), the block matrix that corresponds to $DP_{1.2}$ and $DP_{1.3}$ expresses the system performance. One may presume that the system provides suitable air-conditioning to the room as long as it is up and running. It is therefore possible to evaluate the information content of the system due to the likelihood of failure at low failure rates. Since it is difficult to determine a probability distribution function for the failure rates, a membership function is used instead.

In order to compute the information content associated to the costs, one assumes that the corresponding probability distribution is uniform.

3.4 The FMEA Process

FMEA was used to investigate the likely failures of components in each one of the alternative systems. The following specific rankings were employed: severity effect of the failure (SF), detection and fixing time (DFT), and failure rate (RF_{10}) [Stamatis, 1995]. The potential effects of the failures employed a ranking for the failure severity that ranges from 1 (very small) to 10 (very high) and a ranking for the detection and fixing time going from 1 (immediate) to 5 (very long). Additionally, data from ten years of sales of HVAC systems and spares allowed estimating the rate of failure of the parts

This allows us to determine ranges for the variations of the failures, as well as the average failure values, by mixing statistical estimators and linguistic variables that express the opinions of the after sales personnel. As a bottom line, one could find a loss triangular membership function due to the failures.

Each one of those specific rankings apply to all the components that are likely to fail, so that the overall failure ranking of each component is the product of the specific ranks that are considered. Assuming an independent condition for the failure of each component, the system failure ranking is sum of the components' rankings.

Table 1. Loss triangular membership function for a non-redundant chilled water system (NR_CW).

Component	SF			DFT			RF			Loss		
Compressor	4	5	6	3	5	5	3.0	4.3	5.0	36	108	150
Pump	2	3	4	2	3	5	1.2	2.4	7.0	5	22	140
Leak refrigerant circuit	4	5	6	2	3	5	2.5	3.0	2.5	20	45	75
Condenser fan	1	2	3	0	1	2	4.1	5.3	6.0	0	11	36
Electronics	9	10	10	0	1	2	12.0	21.1	25.0	0	211	500
AC or AHU fan	4	5	6	0	1	2	0.0	0.5	1.0	0	3	12
Evaporator	9	10	10	3	5	5	0.0	0.7	1.0	0	37	50
							Loss triangular membership function			61	436	963

Table 1 contains the severity of failure, the detection and fixing time, the rate of failure and the computed loss triangular membership function [61 436 963], for a non-redundant CW system.

The same technique was used to compute the triangular membership functions for the losses of all the considered design solutions, as shown in Table 2 (where R stands for redundant, NR for non-redundant, CW for chilled water and DX for direct expansion).

Table 2. Loss triangular membership functions.

System	Min	Average	Max
NR_CW	61	436	963
R_CW	0	120	381
NR_DX	131	496	925
R_DX	24	198	484

3.5 The Systems' Information Content

The information content related to the losses was obtained through Eq. (5), which was used to compute the areas depicted in Figure 3 by using the trapezoidal function [0, 50, 150, 200] to represent the design range. Table 3 contains the attained results.

Table 3. Information for losses.

System	Information
NR_CW	4.31
R_CW	0.76
NR_DX	6.12
R_DX	1.73

The information content associated to the costs was computed through a very simple model based on the willingness of the entrepreneur to pay no more than a definite amount per kW of refrigeration power.

Hence, one had to specify the system range for the cost per unit power for every design solution.

The records on the budgets of the 12 data centres that are mentioned in section 3.2 of this paper contain the cost of each component of real HVAC systems used in datacom centres. All those systems are redundant, since all of them feature a chiller backup. Nevertheless, it was easy to recalculate new budgets in the assumption that the four systems under analysis could be either non-redundant or outfitted with DX units. Table 4 displays the ranges of variation of cost for the studied systems as they were calculated.

Table 4. System ranges for cost (values on EU market, do not apply directly to any market).

System	Min (€/kW)	Max (€/kW)
NR_CW	593	867
R_CW	918	1339
NR_DX	557	796
R_DX	824	1187

The information content of cost was computed under a uniform probability density hypothesis, and Figure 6 depicts the sum of the information content due to the costs and to the losses.

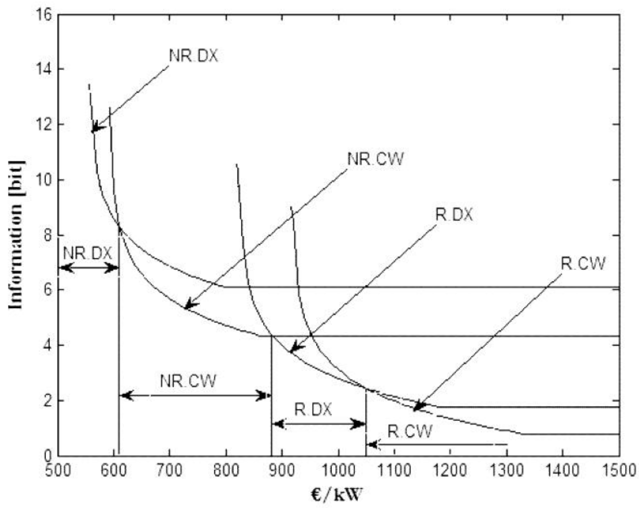

Figure 6. The HVAC systems information content.

Accordingly, the preferred system should be the one with the least information content that fits the target investment that the entrepreneur is willing to do.

Notice that the only data needed for computing the information content are the ranges shown in Table 2 and Table 4 above.

4 CONCLUSION

This paper addresses the usage of the AD's Information Axiom in the process of decision of the best HVAC system to select for datacom centre applications. In addition, it introduces the model of cost as a functional requirement giving place to define the segments of the application for each solution. The four systems under analysis are of the chilled water (CW) and direct expansion (DX) types, both with redundant (R) and non-redundant (NR) variants. The higher-level functional requirements that describe those systems are related to their behaviour, as well as to the losses due to the failure of components and to the cost. The design equations of all the considered systems exhibit a lower triangular or a rhomboid matrix, so that the designs are decoupled.

One employs the concept of conditional information, which allows computing the information content of the systems by using the Bayesian probability concept. This allows calculating the system information content as the sum of the information content of failure losses with the joint information content of cost.

As a result, the range of investment in €/kW for non-redundant direct expansion systems (NR_DX) is up to 610 €/kW; for non-redundant chilled water systems (NR_CW) the range is [610 880]; for redundant direct expansion systems (R_DX) the range is [880 1,050]; and for redundant chilled water systems (R_CW) the range is over 1,050 €/kW.

On the other hand, the R_CW is the system with the less information content, but it requires a minimum investment of 1,050 €/kW.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by Fundação para a Ciência e Tecnologia through the grant PEst-OE/EME/UI0667/2011 - UNIDEMI.

In addition, they acknowledge CEST, Comércio e Indústria, Lda for the helpful contribution of data about failures of components and costs of datacom centres. Their support made this paper worthwhile.

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