

Decision-making on HVAC&R systems selection: a critical review

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Decision-making on HVAC&R systems selection: a critical review

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ABSTRACT

Buildings account for more than 40% of total energy consumption in most countries and more than 55% of this energy is used by heating, ventilation, air-conditioning and refrigeration (HVAC&R) systems. This significant energy demand, together with the global need to impose energy-efficiency measures, underlines the importance of selecting the most appropriate HVAC&R system in the early stages of a design process. However, this state-of-the-art study reveals that there is no review paper available in the open literature to critically analyse the existing methods for HVAC&R systems selection. Therefore, the aim of this paper is to critically review the body of knowledge on the adopted approach for HVAC&R systems selection. Based on the comprehensive literature review, the needs and gaps in this field are identified. It is revealed that the integration of probabilistic climate changes into the decision-making processes is one of the main areas that should be addressed in future studies. In addition, reliability and Life Cycle Cost of the systems, health and well-being, occupants' satisfaction and indoor air quality are of paramount factors that should be taken into account in the decision-making process for HVAC&R systems selection.

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HVAC&R systems; decision-making; building services; energy; environment; building energy efficiency; system selection

1. Introduction

Demands for thermal comfort, better indoor air quality together with lower environmental impact have been increasing in the last decade. In many circumstances, these demands could not be entirely addressed through the soft bioclimatic design approach which optimises the buildings orientation and internal layout and adopts natural ventilation and passive cooling. This is mainly due to the dense urban environment and the internal energy loads of the buildings. In such cases, heating, ventilation, air-conditioning and refrigeration (HVAC&R) systems make a key contribution to fulfil the requirements of the indoor environment. Therefore, to address these demands, while maintaining the buildings energy consumption and the associated CO₂ emissions at acceptable levels, it is of paramount importance to select the most appropriate HVAC&R system.

HVAC&R systems selection is an inherent stage of a building design and construction process. Therefore, investigation into the building design and construction process can help to understand the process of HVAC&R systems selection. An investigation into the design and construction process is also essential in order to identify real deficiencies, needs and gaps in the HVAC&R systems selection process.

Among the several design processes developed within the context of construction and the built environment (Potter 1995; Bejan, Tsatsaronis, and Moran 1996; Parsloe and Wild 1998; Phillips 2008;

Table 1. RIBA Plan of work for building design and construction (RIBA 2013).

Design and construction stages (RIBA plan of work)	
Stage	Descriptions
0	Strategic Definition
1	Preparation and Brief
2	Concept Design
3	Developed Design
4	Technical Design
5	Construction
6	Handover and close out
7	In use

RIBA 2013), ‘Royal Institute of British Architects (RIBA) plan of work’ offers a comprehensive plan for all disciplines involved in the design of construction projects. Table 1 shows the detailed categorisation of design and construction stages of a project as defined by the RIBA plan of work (RIBA 2013).

Strategic Definition is the initial stage in which a project is strategically appraised and defined before a detailed brief is created (RIBA 2013). It includes the identification of the client’s needs and project constraints. In the next stage, Preparation and Brief, all these initial factors are considered to develop project objectives, including quality objectives and project outcomes, sustainability aspirations and project budget, and develop Initial project brief (RIBA 2013).

Concept Design is the next stage of the process which includes the implementation of the project brief into the project concept design. Outline design proposals together with a sustainability analysis forms the key outcomes of this stage (RIBA 2013). Stage three, Developed Design, is to develop the entire project brief to make it ready to be implemented within the Technical Design. In addition, the Developed Design includes coordination of the proposals for structural design, building services systems, outline specifications, cost information and project strategies in accordance with design programme (RIBA 2013).

The design process addressed in the first five stages demonstrate that the initial decision about main elements of the design including HVAC&R systems selection is initially made in the Preparation and Brief by taking into account the clients’ needs and project objectives. This initial decision is gradually refined and regularly reviewed based on the developments in the project up to the end of ‘Developed Design’. During this decision review process, the initial decisions may be changed according to the needs and constraints of the project (RIBA 2013).

The outcomes of studies conducted by Potter (1995), Parsloe and Wild (1998) confirm this approach, as they also emphasised that the HVAC&R systems selection should be conducted in the early stages of any project.

This broad overview of the design process, that revealed the early need for HVAC&R systems selection within the design process, together with the following literature review, provides a basis to identify the deficiencies, needs and gaps in the decision-making process for HVAC&R systems selection.

2. Decision-making for HVAC&R systems selection

The previous studies on decision-making process for HVAC&R systems selection which are available through the open literature (Hitchcock 1991; Shams, Nelson, and Maxwell 1994a; Maor and Reddy 2004; Avgelis and Papadopoulos 2009; Wang, Jing, and Zhang 2009a; Shahrestani, Yao, and Cook 2012) can be categorised into four main groups, which are described in the following sub-sections:

- (1) Studies which are highly detailed and examine both HVAC&R system performance evaluation and decision-making analysis.
- (2) Studies aimed to consider a broad range of alternatives for HVAC&R systems selection.
- (3) Studies aimed to develop a comprehensive model for HVAC&R systems selection.
- (4) Studies which are mainly focused on their adopted decision-making methods.

Here, it should be noted that categorisation and characterisation of HVAC&R systems are beyond the scope of this study and these two subjects have been covered in several references including ASHRAE (2016) and CIBSE (2016).

2.1. The studies which are highly detailed and examine both HVAC&R system performance evaluation and decision-making analysis

One of the investigations on HVAC&R systems selection was conducted by Avgelis and Papadopoulos (2009). A dynamic performance evaluation of alternative HVAC&R systems together with a multiple criteria decision-making process was carried out to choose the most appropriate HVAC&R system. In this study, the energy consumption, thermal comfort, indoor air quality, economic and environmental aspects of the alternatives were evaluated. To assess the technical performance characteristics of the alternative HVAC&R systems, the TRaNsient SYstems Simulation (TRNSYS) software (Klein et al. 2009) was employed. For the HVAC&R systems selection, 'ELimination Et Choix Traduisant la REalité (ELECTRE) III' was adopted as a formal decision-making method (Roy 1996). The final decision was made through consideration of three different economic scenarios/assumptions about the annual changes in the price of energy commodities including crude oil, natural gas and electricity (Avgelis and Papadopoulos 2009). Despite the fact that this study addressed high-demand issues, five main areas of improving HVAC&R systems selection were identified.

- (1) Among the extensive range of HVAC&R systems that are available, only a few alternatives were studied. Those included gas and oil fire boilers, split room air conditioners, hot water radiators, air-cooled chillers and variable volume air distribution system with reheat coils.
- (2) In practice, HVAC&R systems selection has to be conducted in the practical design environment. The approach described by Avgelis and Papadopoulos (2009) is not user-friendly, is too complex, time-consuming and therefore expensive to be adopted in practice.
- (3) The study was focused on an office building in Greece. However, it is unclear if the results might be applicable to other countries with different ambient conditions.
- (4) The energy-related CO₂ emissions were assessed based on the current carbon intensity of the national grid. Whereas, there is an international commitment for electricity decarbonisation (EU Commission 2011) that significantly influences the calculation and consequently, the outcome of any decision-making for HVAC&R systems selection.
- (5) The expected radical climate changes in the future were not considered by Avgelis and Papadopoulos (2009).

The following sub-sections review the studies available in the open literature that have focused to overcome the aforementioned deficiencies of the HVAC&R systems selection approach proposed by Avgelis and Papadopoulos (2009).

2.2. Studies aimed to consider a broad range of alternatives for HVAC&R systems selection

As it was mentioned in the preceding section, considering only a few alternatives for HVAC&R systems selection was the first area for improvement in the valuable study conducted by Avgelis and Papadopoulos (2009). This section describes the previous studies that have attempted to overcome this deficiency.

Maor and Reddy (2004) introduced a knowledge-based system called Knowledge-Based Conceptual Design (KBCD) to automatically synthesise an extensive set of possible alternatives for HVAC&R systems selection. These alternatives were then evaluated by building energy simulator programmes such as DOE-2.1E (Winklemann 1993). In addition, an ownership and maintenance cost module was developed to assess the costs of the synthesised HVAC&R systems. The energy

consumption of the alternative HVAC&R systems which emerged from simulations were used by the cost module to evaluate the Life Cycle Cost (LCC) of the systems. Finally, the alternatives developed by the KBCD model were ranked according to the LCC criterion (Maor and Reddy 2004; Maor, Panjapornpon, and Reddy 2004).

Lack of means for automatically synthesising a variety of possible HVAC&R systems was the rationale behind developing the KBCD model (Maor and Reddy 2004; Maor, Panjapornpon, and Reddy 2004). This model was based on the building architecture and the heuristic knowledge of HVAC&R systems (Maor and Reddy 2004; Maor, Panjapornpon, and Reddy 2004). The heuristic knowledge used in this model refers to the knowledge of experts developed over the years to synthesise the feasible combinations of the existing primary and secondary HVAC&R systems. The building architecture content included the building application, class and geometry together with lighting, equipment and system schedules as well as user constraints and the availability of energy resources. The HVAC&R systems knowledge consisted of the application and configuration knowledge of both the primary and secondary systems. Finally, the ownership and maintenance costs were acquired from a range of references such as Mossman, Plotner, and Babbitt (2002).

Despite the robustness of the KBCD model to generate a broad range of HVAC&R alternative systems which could be analysed using the existing simulation programs, there are some areas for potential improvement.

- In general, the limited time to evaluate alternatives within a conceptual design makes it difficult to justify a detailed examination and compels designers to ignore consideration and study of all the potential alternative systems (Elovitz 2002). Although the proposed method was planned to reduce the time taken to review alternative systems, it includes another time-consuming task, the evaluation of a range of alternatives by an accurate hourly analysis program (such as DOE-2). Therefore, despite the value of generating a broad range of alternatives and transforming them into simulation programs, the evaluation of many alternatives is not feasible within the limited time for decision-making at the early stages of a project (Elovitz 2002).
- In the KBCD model developed for HVAC&R systems selection, the LCC was the only criterion to evaluate the performance of HVAC&R systems. The lack of consideration of the environmental impact and the influence of HVAC&R systems on indoor environment raises concerns over the robustness of results produced by this model.
- The influences of climate change and global warming on buildings and HVAC&R systems were not considered in the knowledge-based model for systems selection.

2.3. Studies aimed to develop a comprehensive model for HVAC&R systems selection

As was mentioned in Section 2.1, the second and third deficiencies of the HVAC&R systems selection approach proposed by Avgelis and Papadopoulos (2009) were around the concerns about the applicability of the proposed approach for designers and decision makers and its failure to consider a broad range of climate conditions in the decision-making process. This section examines some of the studies that have attempted to overcome these two deficiencies through the development of a comprehensive model for HVAC&R systems selection.

Finch (1989) established a framework to analyse and justify design decisions for mechanical and electrical services in buildings. This study was one of the earliest attempts to make comprehensive decisions by providing explicit assumptions and generating a transparent decision-making process. Despite the strengths of this study on providing a framework for decision-making in building services, there are some areas for potential improvement:

- Only seven alternative primary HVAC&R systems were considered in the decision-making.

- In a multiple attribute decision-making, the evaluation of the performance of each alternative system with respect to each attribute is the most important part of the process. In the study conducted by Finch (1989), the source of these performance evaluations was not explicitly described.
- Energy consumption and the energy-related CO₂ emissions of the alternative HVAC&R systems were not included within the attributes considered in the decision-making process.
- The proposed approach was not simple and the implementation of such an approach would need a great deal of time and investment. This raises concerns about the applicability of such an approach to the decision-making stages in building services design. This might be the rationale behind the trend of the subsequent studies in this field (Camejo and Hittle 1989; Fazio, Zmeureanu, and Kowalski 1989; Hitchcock 1991; Shams, Nelson, and Maxwell 1994a; Maor, Panjapornpon, and Reddy 2004) which moved towards the knowledge-based systems in order to reduce the complexity of the decision-making processes.

Camejo and Hittle (1989) introduced an expert system which included five knowledge-based subsets for HVAC&R system design. Expert systems are computer programs that seek to mimic the human reasoning (Camejo and Hittle 1989). The information about the human reasoning when addressing a specific decision is the core element of expert systems and these are held in the knowledge-based part of an expert system. In the expert system proposed by Camejo and Hittle (1989), the first subset attempted to identify a few, at least two, possible HVAC&R systems based on the limited inputs about the type of building, number of floors and rooms and the geographical location of the building. This subset estimated some of the principal parameters associated with the proposed systems. The parameters were estimated based on a fast rule of thumb, although not entirely accurate, and include installation/operation cost, required power, system life time and the required space.

The second subset was designed to detect flaws in a project design and also to produce a range of recommendations. These could address the poor use of glazing or an inappropriate insulation value based on the information contained in occupancy profiles and density together with information about the physical properties of construction elements and the building internal heating load. In the third knowledge-based subset, the system parameters that had been estimated in the first subset were assessed in a more accurate manner based on the user defined building energy demand and the energy load profile together with other project information such as the type of building. The fourth and fifth knowledge-based subsets were used to select the HVAC&R components and the system control strategies. These two knowledge-based subsets included the information from manufacturers about the HVAC&R components and their control approach (Camejo and Hittle 1989). Despite the novelty of the well-structured multiple knowledge-based expert system provided by Camejo and Hittle (1989), the following deficiencies are identified:

- The expert system was based on simple rules of thumb and heuristic knowledge. The main concern here is that by applying simple rules of thumb, this could result in wrong decisions (Shaviv and Peleg 1990). Consequently, these inappropriate decisions could not be easily overcome during the next stages of the design and construction phases (Treado et al. 1986).
- It was not clearly defined whether this tool is only applicable to a specific region in the U.S. or that may also be used for buildings in other regions with different climate conditions.
- It was not clear how HVAC&R systems were selected when using a range of criteria in the first knowledge-based subset.
- The environmental impacts of HVAC&R systems and the quality of indoor environment were not taken into account within the systems selection process. Also, the impact of climate change on HVAC&R systems selection was not addressed in the decision-making process.

Another study to establish an expert model for HVAC&R systems selection is the prototype knowledge-based model (SELECT-HVAC) generated by Fazio, Zmeureanu, and Kowalski (1989). This model was built using a knowledge-based model generator called ESCHER (Fazio, Zmeureanu,

and Kowalski 1989). In general, to develop a knowledge-based model a knowledge engineer and a domain expert are required (Fazio, Zmeureanu, and Kowalski 1989). Domain expert is responsible to find and categorise the required knowledge about the configuration of HVAC&R systems from available resources in the field. The responsibility of the knowledge engineer is to transfer the knowledge of domain experts into a knowledge-based model. The ESCHER was developed so that domain experts could directly transfer the knowledge into it (Fazio, Zmeureanu, and Kowalski 1989).

The selection and configuration of the components of air distribution systems, that is, heating and cooling coils, preheat coils, filters and fans, were the main focus of the SELECT-HVAC model developed by Fazio, Zmeureanu, and Kowalski (1989). The SELECT-HVAC model integrated the expert knowledge about the applicable configurations, while simultaneously considering the assembly rules of different components for air distribution systems, together with psychrometric analysis to determine the nature of the heating/cooling and humidification/dehumidification processes (Fazio, Zmeureanu, and Kowalski 1989). The SELECT-HVAC model was able to configure the main components of an air distribution system by taking into account indoor/outdoor design conditions, building thermal loads of heating/cooling, building type, activity and the schedule of operation.

Capturing of the experts' knowledge and the integration of this knowledge into psychrometric analysis produced a strong tool for the automatic selection and configuration of the components within an air distribution system. Also, this model can be applied to different weather conditions. However, there are some deficiencies in the proposed SELECT-HVAC model as listed below:

- The proposed model was only applicable to air distribution systems and the primary elements of HVAC&R systems were not covered. In addition, very few secondary systems were considered in the model.
- It was not clear how rigorously the domain (expert) knowledge had been acquired. Concerns over the reliability of domain knowledge became more apparent in the study conducted by Shams, Nelson, and Maxwell (1994a). This study revealed that, in many cases, there is no general agreement about the preferred systems between experts and the open literature.

Another study in this field was conducted by Hitchcock (1991), which aimed to develop a knowledge-based model for HVAC&R system design. This knowledge-based system starts with a set of questions regarding building size, climate region and available energy sources (Hitchcock 1991). Then, a database adopted from BHKRA (1985) is utilised to evaluate energy consumption and cost. The database includes energy consumption and cost estimation figures of various combinations of climate conditions, building size, HVAC&R system types, glazing area percentages and energy sources. Finally, the fully developed knowledge-based system was able to provide a range of technical suggestions which could be included in the building design and make a decision about HVAC&R systems selection. The technical suggestions provided by this model were based on the combination of the rules of thumb, database queries and mathematical calculations.

The model provided several alternative HVAC&R systems together with a rank order through a process of asking few questions from users (Hitchcock 1991). This is quite reasonable and desirable in order to facilitate decision-making in the early stages of a project and underlines the applicability of this model within the overall design process. Also, the credibility of the background database which had been developed by BHKRA (1985) and was based on numerous computational simulations and crosschecked by experts for a variety of weather conditions was the key strength of this knowledge-based model. However, there are some deficiencies in the proposed knowledge-based model, which include:

- The environmental impact of different HVAC&R systems was not considered in the decision-making process for HVAC&R systems selection.
- The influence of climate change and global warming on the design of buildings and HVAC&R systems was not considered in the proposed knowledge-based model.

Shams, Nelson, and Maxwell (1994a, 1994b) developed a knowledge-based model for HVAC&R systems. In this work, knowledge acquisition was achieved through personal interviews, literature reviews and case studies. The aim of this research was to select the main components of HVAC&R systems for office buildings in two climate regions, cold and hot/humid, through capturing of the decision makers' thought process.

During the first round of interviews, it emerged that a significant numbers of interviewees answered the questions in a general form and commonly at a tangent to the topic under discussion due to the nature of the interview. However, to develop the rules for this knowledge-based system, it was essential to capture the chronology of the decision makers' thought process (Shams, Nelson, and Maxwell 1994a). In order to overcome this issue, in the second round of interviews, the prioritisation of the criteria for HVAC&R systems selection and the consequences of these priorities on the final decisions were examined. In addition, the steps required to develop the structure of this knowledge-based model, such as the identification of objectives and their relative importance, were also discussed (Shams, Nelson, and Maxwell 1994a).

Analysis of the findings from interviews revealed that there are many different points of view between interviewees regarding some identical issues. Further analysis showed that the previous experience of the interviewees played a key role in these differences. It was also established that there are several important differences between the recommendations contained in the technical literature and the decision makers' thought process (Shams, Nelson, and Maxwell 1994a). For instance, although water source heat pump systems can offer a very high level of energy efficiency to the building, in general, experts held a very negative view of this system and none of them would positively recommended it. Further analysis showed that poor manufacturing quality was the main reason behind this negative view (Shams, Nelson, and Maxwell 1994a).

In the proposed knowledge-based model for HVAC&R systems selection developed by Shams, Nelson, and Maxwell (1994a, 1994b), a range of HVAC&R systems were considered including Constant Air Volume (CAV), Variable Air Volume (VAV) Multi-zone, the VAV with reheat, radiant heating systems, water source heat pumps, packaged terminal air conditioners and fan coil units. To choose the most appropriate system within these alternatives, the following criteria were used: ease of maintenance, cost including capital installation and maintenance cost, future flexibility, humidity control, individual zone control, indoor air quality, sound power level, loss of usable floor space, degree of periodic maintenance in occupied spaces and the general outdoor appearance (Shams, Nelson, and Maxwell 1994a).

The proposed decision-making model was a user-friendly tool due to the intrinsic nature of the knowledge-based models (Shams, Nelson, and Maxwell 1994b). The model considered two climate regions, cold and hot/humid. However, the deficiencies in the developed knowledge-based mode included:

- Only two primary HVAC&R systems were considered, as the model was firmly focused on the secondary part of HVAC&R systems. Due to the strong inter-dependency between primary and secondary systems, there are concerns about selection process which chooses secondary systems without considering their associated primary parts.
- The environmental aspects of HVAC&R systems were not considered.
- The climate change and global warming were not considered in the decision-making process.
- The rank order of the alternative systems with respect to different criteria was addressed in this study. However, it was not clear how the subjective weight for each criterion was developed based on the data drawn from designers and decision makers who exposed different points of view about the priorities and weights of the criteria for HVAC&R systems selection.

Korolija et al. (2009) conducted a HVAC&R systems selection study for office buildings in the UK. In this research, a case-study prototypical office building with two sets of fabric specifications was investigated. For the first case, and in order to represent a building with a low level of insulation,

the specifications of building fabric were defined as those which would meet the requirements of the UK 1990 Building Regulations (DCLG 1990). For the second case, to represent an office building with acceptable level of insulation, the specifications of the building fabric were defined according to the UK 2006 Building Regulations (ODPM 2006).

In this study, the HVAC&R system selection was carried out by considering just a few alternative HVAC&R systems including; the CAV and VAV with/without economiser. Simultaneous performance evaluation of the HVAC&R systems and the conditions experienced in the case-study buildings was conducted through a series of simulations using the EnergyPlus software (EnergyPlus 2011). To evaluate the performance of the studied HVAC&R systems, the energy consumption and the energy-related CO₂ emissions of the systems were taken into account.

Despite the valuable approach adopted in this study by simultaneous dynamic simulation of a building and HVAC&R systems, there are some deficiencies that include:

- The secondary systems were mainly considered and the primary parts of the systems were not included in the selection process.
- Although the prototypical building that was used could be assumed to be representative of office buildings in the UK, the simulation only involved the London weather conditions. It was not clear whether the results could be extended to other regions in the UK.
- Only energy consumption and energy-related CO₂ emissions of the HVAC&R systems were taken into account in the selection process and the economic aspects of the systems, that are of significant importance for HVAC&R systems selection, were not considered.

The climate change and global warming were not considered within the process of decision-making for HVAC&R systems selection.

Shapiro and Umit (2011) conducted a study into HVAC&R systems selection for envelope-dominated buildings. In this study, four different HVAC&R systems were considered including; air source heat pump, ground source heat pump, boiler and water source heat pump with cooling tower and finally, a boiler with an associated chiller. To rank these alternatives, the energy-related CO₂ emissions were taken into account. In order to evaluate the performance of the alternative HVAC&R systems, they were virtually installed in a prototypical building and the performance of both the building and the HVAC&R systems was simulated using the eQuest (V3.64) software. These simulations were conducted within four different climate conditions; mixed humid (New York), warm humid (Atlanta), warm dry (Las Vegas) and cool humid (Chicago) (Shapiro and Umit 2011).

Although an interesting systematic study was conducted for the evaluation of energy consumptions and the associated carbon emissions, there are some deficiencies associated with this research:

- Only four HVAC&R systems were evaluated and ranked in this study.
- Because the focus of this study was mainly on primary HVAC&R systems, the secondary systems were not taken into account.
- The climate change, global warming and plans to mitigate their consequences were not taken into account.
- Only the energy-related CO₂ emissions of HVAC&R systems were taken into account and the important economic aspects of HVAC&R systems were not considered.

2.4. Studies which are mainly focused on their adopted decision-making methods

This section is dedicated to the previous studies in the field of HVAC&R systems selection which were mainly focused on their adopted decision-making methods.

Thiel and Mroz (2001) conducted research into the selection of heating systems for museums. In this study, three alternative heating systems were considered including, gas-fired boiler, oil-fired

boiler and electrical heating system. Five criteria were defined to evaluate the systems. These criteria were energy consumption, system durability, practical installation difficulties, insurance cost and total cost which include investment and operation costs. To perform a formal multiple criteria decision-making process, the ELECTRE III method (Roy 1996) was adopted. The outcome of this study revealed that, despite the significant lower running costs offered by the first two alternatives, the electrical heating system was selected as the most appropriate heating system. This alternative was selected mainly due to its high score with respect to its ease of installation which was the most important criterion for the decision makers. In addition, high durability of this system, which is of paramount importance for museums, was a contributing factor for this decision (Thiel and Mroz 2001).

Despite the advantages of Thiel and Mroz (2001) systematic decision-making model, which included the quantification of some qualitative criteria, there are deficiencies in this research:

- There is a concern over the reliability of the simplistic approach, which is used to qualitatively evaluate the system durability and practical installation difficulties for heating systems selection.
- The alternatives only included primary heating systems and no distribution systems were considered.
- The environmental impacts of the heating systems were not taken into account.
- The climate change and global warming were not taken into account within the process of heating systems selection.

Wang et al. (2008) developed a decision-making model to select an optimal cold storage system for air-conditioning systems. In this study, four alternatives were investigated. The first three alternatives were: ice cold storage, chilled water cold storage and Phase Change Materials cold storage. These systems were designed to respond directly to the cooling demand. However, the fourth alternative was a chilled water cold storage that was designed to subcool the liquid refrigerant leaving the condenser of the refrigeration cycle. This subcooling process improves both the energy performance and cooling capacity of the cooling system and indirectly contributes to the delivery of chilled water demand (Chen et al. 2006).

These four alternatives were evaluated by considering eight qualitative and quantitative criteria comprising, cooling density, refrigeration coefficient, total investment, technical reliability, systems complexities, floor space, total heat efficiency and cooling capacity. In this study, fuzzy method was adopted to make formal decisions. To evaluate the alternatives with respect to each criterion, the outcomes of another study (Yu 2002) were used. But priority weights of the criteria were compiled using fuzzy linguistic scales. Even though this research was only focused on a specific component of HVAC&R systems, the adoption of the fuzzy decision-making model to reduce the uncertainties associated with the decision-making process is the most highlighted advantage of this study.

In another study with a clear focus on the decision-making process of systems selection, Wang, Jing, and Zhang (2009b) conducted a study into Combined Heat and Power (CHP) systems selection. In this study, 16 types of CHP systems were investigated through the consideration of eight criteria including: efficiency, CO₂ emissions, economic social footprint, installation, maintenance, fuel, electricity and heating costs. The alternative systems were evaluated with respect to each criterion using the outcomes from another study (Pilavachi et al. 2006). This study provides a comprehensive discussion around fuzzy decision-making and use of different weighting methods together with a critical review over the adoption of the fuzzy decision-making method for evaluation of both qualitative and qualitative criteria. Despite all these strengths, there are some deficiencies which are listed below:

- Only CHP systems were investigated and the influence of secondary systems on the dynamic performance of CHP systems was not addressed.

- Climate change and national or international plans to mitigate its consequences, such as electricity decarbonisation, which have a substantial influence on the energy efficiency and the justification for adopting a CHP system, were not considered.
- It is not clear whether the outcomes of this study are only applicable to a specific climatic condition or whether it could be extended to other regions.

Wang, Jing, and Zhang (2009a) also developed a fuzzy decision-making model for HVAC&R systems selection. In this study, six alternative systems were considered including: CAV and VAV, fan coil, induction unit, distributed HVAC&R system (air conditioner) and Variable Refrigerant Volume (VRV). These alternatives were evaluated considering 16 different qualitative and quantitative criteria drawn from the knowledge of experts in the field. These are maturity, temperature control, humidity control, investment cost, operation and maintenance cost, service life, noise pollution, visual impact, space used, cleanliness, fresh air, thermal comfort, convenience, simplicity, concentration and flexibility. These criteria were then weighted against a set of subjective factors. The alternatives were evaluated with respect to each of the criterion based on experts' knowledge. Finally, a fuzzy decision-making method was used to rank the alternative systems. Despite the detailed analysis involved in the decision-making process of this study, there are some deficiencies:

- This study concentrated on secondary HVAC&R systems and the influence of primary systems was not considered.
- Energy consumption and carbon emissions of the systems were not considered.
- The influence of climate change and global warming was not taken into account in the decision-making process.
- It was not clear whether the outcome of this study is applicable to a specific climate or region or could be extended to other regions.
- It was not clear how the evaluation of alternative systems with respect to each criterion was performed. This is a particularly important deficiency. The study by Shams, Nelson, and Maxwell (1994a) revealed that, in many cases, there is no general agreement about any preference of systems between experts and that which is discussed in the literature.

Chinnes, Nardin, and Saro (2011) carried out a decision-making study for heating systems selection in industrial buildings. In this study, eight combinations of primary and secondary heating systems were investigated through the consideration of nine criteria including: reliability, time to repair, lead time (the time between placing an order and the system installation), energy source flexibility, and layout flexibility, comfort, and economic uncertainty, operation and investment costs. For the decision-making part of this study, an Analytical Hierarchy Process (AHP) was adopted (Saaty 1990). For each alternative system, all the criteria except energy consumption and cost estimations were qualitatively evaluated through an interview process involving HVAC&R system design experts. Also, the weighting of the criteria was based on the subjective views of experts. Despite considering eight alternatives and a broad range of criteria for systems selection, following are the main deficiencies in this study:

- There is a concern about the reliability of the qualitative evaluation of the criteria for each alternative system. The study conducted by Shams, Nelson, and Maxwell (1994a) revealed that, in many cases, there is no general agreement about preference of the systems between experts and that which is shown in the literature.
- To evaluate the energy consumption of the alternative systems, the degree-days method was used. However, neither the design efficiency nor the off-design efficiency of alternative HVAC&R systems was specified. In addition, no information was provided about how the base temperature of the studied building was defined. These deficiencies raise the concerns about the reliability of the evaluation of the energy consumption criterion in this study.

- The consistency of the comparison matrix for decision-making was not clearly examined. This is of significant importance in a decision-making process using the AHP method (Saaty 1990).
- The influence of climate change and global warming were not taken into account in the decision-making process.
- It was unclear whether the outcomes of this study are applicable to a specific climate/region or could be extended to other regions.

In another study, Arroyo et al. (2016) implemented a new approach of decision-making, the so-called 'Choosing By Advantages' (CBA), in order to select the most appropriate HVAC&R system for a net zero energy museum. Decision-making using CBA is solely based on the advantages of alternatives. In this approach, the decision makers/stakeholders should assess the importance of these advantages. Finally, the alternatives are ranked based on their total allocated importance weights. Simplicity is a unique advantage of the CBA method used for HVAC&R systems selection by Arroyo et al. (2016). However, there are deficiencies associated with the CBA method and the way in which the method is applied to the studied case.

The main concern is about the weighting approach used in the CBA method to assess the importance of the advantages associated with each alternative. Considering the fuzziness of the weights, allocation of weights without providing the maximum and minimum of the scale is a real source of uncertainty in the results. In addition, it should be noted that the preference/importance is a relative term, which is originally expressed in linguistic terms. The proposed CBA method was not capable of dealing with this fuzziness and failed to introduce a mechanism to reflect linguistic terms into crisp numbers/values. In addition, in the case-study decision-making conducted by Arroyo et al. (2016), only three primary alternative systems were considered. Also, it was not clear how the importance of the advantages associated with each alternative was assessed. Moreover, the expected lifetime of the alternative systems used for net present value calculation and the way in which the CO₂ emissions associated with each alternative was determined were not clearly defined.

2.5. Summary

All the aforementioned studies have made significant contributions to the field of HVAC&R systems selection. Among them, the study performed by Avgelis and Papadopoulos (2009) is of a very high quality. This study was based on robust approach to the detailed and reliable performance evaluation of HVAC&R systems and included a detailed and accurate formal decision-making process. However, this research did not cover a wide range of alternative HVAC&R systems and also it was very complicated, which made it difficult to be applied to other climatic conditions in practice. Besides, the climate change and global warming were not taken into account within the process of decision-making (Avgelis and Papadopoulos 2009). In order to consider a broad range of alternatives within the HVAC&R systems selection process (the second category of literature in this field), Maor, Panjapornpon, and Reddy (2004) introduced a knowledge-based model. However, this study only took into account the LCC criterion, while other influential parameters, for example, the environmental impact of HVAC&R systems, climate change and global warming, were not considered (Maor and Reddy 2004; Maor, Panjapornpon, and Reddy 2004).

The third category of HVAC&R systems selection studies aimed to develop comprehensive models that (a) covered a broad range of environmental conditions and (b) were applicable to an HVAC&R systems selection process. To achieve this aim, two approaches were adopted. In the first approach, knowledge-based models were developed to mimic the decision makers' thought process in performance evaluation and ranking of the alternative HVAC&R systems, as well as the selection of the most appropriate system (Camejo and Hittle 1989; Fazio, Zmeureanu, and Kowalski 1989; Finch 1989; Shams, Nelson, and Maxwell 1994a). In the second approach, simulation programmes were used to evaluate the performance of alternative systems with respect to each criterion (Hitchcock 1991; Korolija et al. 2009; Shapiro and Umit 2011). The outcomes of the knowledge-based

models revealed that, despite the useful applicability of these simplified models for design decision makers, the experts' knowledge was, in many cases, conflicting. This was not only between different experts but also between the experts and the open literature (Shams, Nelson, and Maxwell 1994a), which seriously questions the verification of the knowledge-based models.

Finally, the review of the studies that were mainly focused on their decision-making methods (the fourth aforementioned category of literature in this field) revealed that, in most of the cases, the adopted decision-making methods were the core of the study. In other words, little effort was dedicated to the reliability of the performance evaluation of alternative systems with respect to each criterion, and also to provide a means to extend the scope of the proposed decision-making model to other regions with different climatic conditions.

The attributes of the previous studies, including the criteria and alternatives considered in HVAC&R systems selection, are, respectively, demonstrated in Tables 2 and 3. Furthermore, Tables 4 and 5 show the climatic regions and the adopted evaluation methods used in the previous studies to evaluate the performance of alternative HVAC&R systems with respect to each criterion.

Review of the open literature revealed that HVAC&R systems selection process includes the performance evaluation of a few alternatives to choose the best solution (Maor 2002). This process can be significantly influenced by time and knowledge and relies on the designers' experience and their capabilities. The lack of time and knowledge often culminates in ignoring some potential alternatives (Maor 2002; Maor, Panjapornpon, and Reddy 2004). It may also result in a wrong decision which could be very difficult to rectify in the next stages of the design and construction process (Treado et al. 1986). In addition, the challenges associated with the approval of the design recommendations by the clients is compounded by their lack of time and knowledge. Clients have to make sure that the recommended proposal complies with the requirements of the project. However, they are compelled to rely on suitably competent designers' and advisors' recommendations to avoid wasting a great deal of time and effort (Langmaid 2004).

This situation is becoming much more challenging where the design needs to meet the ASHRAE requirements. ASHRAE (2016) states that 'the design engineer is responsible for considering various systems and recommending one or more systems that will meet the project goals and perform as desired'. The consideration and evaluation of several systems rather than just a few alternatives make the decision-making process for HVAC&R systems selection more challenging.

Ever since the energy crisis of 1973, numerous simulation tools have been developed to evaluate the performance of HVAC&R systems. Some of the developed tools include DOE-2 (Bridsall et al. 1990), AXCESS (Howell and Sauer 1975), HAP E20-II (Carrier 2009), BLAST (Lawrie 1992), TAS (Gough 1986), TRACE (Althof 1987), HVACSIM+ (Clark, William, and May 1985), TRNSYS (Beckman 1994), QUICK control (Mathews, van Heerden, and Arndt 1999a, 1999b) and EnergyPlus (EnergyPlus 2011). The main advantage of utilising these tools is to evaluate and compare the energy consumption and indoor environmental conditions associated with different HVAC&R systems. Unfortunately, most of them are difficult to use and are more suited to researchers and not to system designers. In addition, these tools have a long running time which is a disadvantage for designers. Moreover, decision-making processes are not integrated in these simulation tools and therefore can only provide information that could be used as inputs for a separate decision-making process.

In terms of criteria for decision-making, despite considering a broad set of attributes in the previous studies (Table 2), reliability and LCC of the systems, indoor air quality and noise control, health and well-being are the most important factors which have received least attention in the process of HVAC&R systems selection. To make a better decision, LCC should be analysed for each stage of equipment's life from cradle to grave (Wu et al. 2006; Clements-Croome 2013). Even though thermal comfort is addressed in the previous studies for systems selection, 'well-being' is a more comprehensive term which is beyond the environmental comfort (Ong 2013). Building moderate climates, with enough fresh air and least odours, noise and pollution are important factors in keeping the occupants healthy and enhance well-being (Clements-Croome 2013). There is clear evidence in the open literature that suggests that productivity tends to be increased by enhancement in the

Table 2. Criteria for analysis and decision-making in the previous HVAC&R systems selection studies.

Category (Note A)	Study														
	1	2	3							4					
	Avgelis and Papadopoulos (2009)	Maor, Panjapornpon, and Reddy (2004)	Finch (1989)	Camejo and Hittle (1989)	Fazio, Zmeureanu, and Kowalski (1989)	Hitchcock (1991)	Shams, Nelson, and Maxwell (1994a)	Korolija et al. (2009)	Shapiro and Umit (2011)	Thiel and Mroz (2001)	Wang et al. (2008)	Wang, Jing, and Zhang (2009b)	Wang, Jing, and Zhang (2009a)	Chiness, Nardin, and Saro (2011)	Arroyo et al. (2016)
Criteria															
Energy use	✓			✓	✓	✓		✓		✓					
CO ₂ emissions	✓							✓	✓			✓			✓
Thermal comfort	✓												✓	✓	
Management convenience													✓		
Indoor air quality	✓						✓								
Fresh air													✓		
Clean lines													✓		
LCC		✓	✓												
Operating cost	✓			✓		✓	✓		✓		✓ ^E	✓	✓	✓	
Maintenance cost	✓						✓		✓		✓	✓	✓		
Insurance cost									✓						
Investment cost	✓			✓			✓		✓	✓	✓	✓	✓	✓	
Life time				✓					✓			✓	✓		
Ceiling space requirement			✓												
Required space				✓							✓		✓		✓
Building type					✓										
Operation schedule					✓										
Building size					✓	✓ ^H									
Indoor/outdoor design conditions					✓	✓ ^H									
Available energy sources					✓	✓ ^H									
Energy source flexibility														✓	
Ease of maintenance							✓								
Low maintenance in the occupied space							✓								
Implementation difficulties									✓						
System complexity										✓					
Simplicity											✓				
Time required of repair													✓		
Lead time														✓	✓ ^G
Future flexibility							✓								

(Continued)

Contribution to net zero energy	✓
Water consumption	✓
Maintainability	✓

Notes: A. Category 1 Studies which are highly detailed and examine both HVAC&R system performance evaluation and decision-making analysis. Category 2 represents the research studies that aimed to cover a broad range of alternatives. Category 3 comprises the studies that attempted to develop a comprehensive model. Category 4 covers the Studies which are mainly focused on their adopted decision-making methods. B. Floor space encroachment: the distance is in metres from the sidewalls, occupied by facility. C. Perimeter partition flexibility: whether the configuration of Perimeter partition is limited or flexible and if it is flexible, to what extent. D. Module integration: whether the choice of components is restricted by consideration of compatibility. E. In that study, the operation cost includes fuel cost, electricity cost, heat cost. F. Economic uncertainty: the likelihood that real economic partners will significantly differ from estimated ones, for example, due to unexpected increase in installation or fuel costs. G. Lead time: the period of time between placing an order and having the system installed and functioning in site. H. These parameters are used to estimate the energy consumption and the operation cost.

Table 3. Considered alternatives in the previous HVAC&R systems selection studies.

Category	Study														
	1	2	3							4					
	Avgelis and Papadopoulos (2009)	Maor, Panjapornpon, and Reddy (2004)	Finch (1989)	Camejo and Hittle (1989) +	Fazio, Zmeureanu, and Kowalski (1989)	Hitchcock (1991) +	Shams, Nelson, and Maxwell (1994a)	Korolija et al. (2009)	Shapiro and Umit (2011)	Thiel and Mroz (2001)	Wang et al. (2008)	Wang, Jing, and Zhang (2009b)	Wang, Jing, and Zhang (2009a)	Chiness, Nardin, and Saro (2011)	Arroyo et al. (2016)
Alternatives															
Gas fire boiler	✓	✓							✓	✓				✓	✓
Oil fire boiler	✓									✓					
Split room air conditioner	✓	✓													
Air-cooled chiller	✓	✓		✓					✓						
Water cooled chiller															✓
Absorption chiller		✓													
VAV system	✓	✓	✓	✓	✓	✓	✓	✓					✓		
VAV with terminal reheat	✓	✓	✓				✓								
Fan coil		✓	✓	✓			✓						✓		
Multi-zone		✓					✓								
DOAS with fan coils			✓												
CAV system		✓		✓	✓	✓	✓	✓					✓		
DX package unit		✓		✓		✓	✓								
Split air-cooled heat pump						✓							✓		
Economiser		✓						✓							
Reheat system		✓	✓				✓								
Double duct VAV			✓												
Residential equipment							✓								
Water source heat pump		✓				✓	✓		✓						✓
Air source heat pump									✓						
Ground source heat pump									✓					✓	
Electrical heating system										✓					
Four types of cooling storage											✓				
16 types of CHP unit												✓			
Induction unit			✓										✓		
VRV													✓		
Gas burner														✓	
Floor/wall radiant system														✓	
Hot water radiator panel	✓													✓	
Hot water air heater														✓	
Radiant modules														✓	
Radiant tube														✓	

Notes: Category 1 Studies which are highly detailed and examine both HVAC&R system performance evaluation and decision-making analysis. Category 2 represents the research studies that aimed to cover a broad range of alternatives. Category 3 comprises the studies that attempted to develop a comprehensive model. Category 4 covers the Studies which are mainly focused on their adopted decision-making methods.

+: All alternatives considered in this model have not been explicitly defined in the paper.

Table 4. Regions/weather conditions covered in the previous HVAC&R systems selection studies.

Category	Study	Region covered (climate)
1	Avgelis and Papadopoulos (2009)	Thessaloniki-Greece
2	Maor, Panjapornpon, and Reddy (2004)	Any region (Climate)-simulation is needed
3	Finch (1989)	Not defined
	Camejo and Hittle (1989)	Not defined
	Fazio, Zmeureanu, and Kowalski (1989)	Any region (Climate)-embedded psychrometric calculation is needed
	Hitchcock (1991)	All around the US
	Shams, Nelson, and Maxwell (1994a)	Cold Hot/Humid
	Korolija et al. (2009)	London-UK
	Shapiro and Umit (2011)	New York (Mixed humid), Atlanta (Warm humid), Las Vegas (Warm dry), Chicago (Cool humid)
4	Thiel and Mroz (2001)	Pszczyna-Poland
	Wang et al. (2008)	Not explicitly defined
	Wang, Jing, and Zhang (2009b)	Not explicitly defined
	Wang, Jing, and Zhang (2009a)	Not explicitly defined
	Chiness, Nardin, and Saro (2011)	Not explicitly defined
	Arroyo et al. (2016)	San Francisco, US

Notes: Category 1 Studies which are highly detailed and examine both HVAC&R system performance evaluation and decision-making analysis. Category 2 represents the research studies that aimed to cover a broad range of alternatives. Category 3 comprises the studies that attempted to develop a comprehensive model. Category 4 covers the Studies which are mainly focused on their adopted decision-making methods.

occupants' satisfaction and well-being (Clements-Croome 2006). Importance of productivity of buildings' occupants on LCC of the buildings could be reflected on the ratio of cost associated with HVAC&R systems. Based on the cost database related to a range of 20 different HVAC&R

Table 5. The techniques used in the previous HVAC&R systems selection studies to evaluate alternatives.

Category	Study	Method of evaluation of alternatives with respect to each criterion
1	Avgelis and Papadopoulos (2009)	Quantitative: numerical simulation and cost estimation
2	Maor, Panjapornpon, and Reddy (2004)	Quantitative: numerical simulation and cost estimation
3	Finch (1989)	Qualitative: knowledge acquisition from experts Quantitative: cost estimation
	Camejo and Hittle (1989)	Qualitative: knowledge acquisition from experts and basic rules of thumb Quantitative: cost estimation
	Fazio, Zmeureanu, and Kowalski (1989)	Qualitative: knowledge acquisition from experts and publications Quantitative: psychrometric analysis
	Hitchcock (1991)	Quantitative: numerical simulation and cost estimation
	Shams, Nelson, and Maxwell (1994a)	Qualitative: knowledge acquisition from experts and publications Quantitative: cost estimation
	Korolija et al. (2009)	Quantitative: numerical simulation
	Shapiro and Umit (2011)	Quantitative: numerical simulation
4	Thiel and Mroz (2001)	Qualitative: knowledge acquisition from experts and publications Quantitative: cost estimation and numerical simulation
	Wang et al. (2008)	It is based on secondary data developed by Yu (2002)
	Wang, Jing, and Zhang (2009b)	Qualitative: knowledge acquisition from experts and publications Quantitative: cost estimation
	Wang, Jing, and Zhang (2009a)	Qualitative: knowledge acquisition from experts Quantitative: cost estimation
	Chiness, Nardin, and Saro (2011)	Qualitative: knowledge acquisition from experts Quantitative: estimation of energy consumption using degree-days method plus cost estimation
	Arroyo et al. (2016)	Qualitative: knowledge acquisition from experts and publications Quantitative: cost estimation

Notes: Category 1 Studies which are highly detailed and examine both HVAC&R system performance evaluation and decision-making analysis. Category 2 represents the research studies that aimed to cover a broad range of alternatives. Category 3 comprises the studies that attempted to develop a comprehensive model. Category 4 covers the Studies which are mainly focused on their adopted decision-making methods.

systems, Wu and Clements-Croome (2007a) have shown a ratio of cost of 1:7.7:78.9, where for each pound spent for the initial cost of the systems, £7.7 are spent for maintenance and operation and £78.9 on staffing. It should be noted that this ratio is just provided as an indication and using a constant ratio in LCC analysis might result in making wrong decisions.

In addition, despite vast developments on control strategies for HVAC&R systems in the last decade (Dounis and Caraiscos 2009; Oancea and Caluianu 2013; Mirakhorli and Dong 2016), the way in which systems are controlled has not been seriously considered as a criterion for systems selection in the reviewed studies. In reality, the level of energy performance, indoor air quality, environmental impacts and occupants' well-being associated with HVAC&R systems highly depend on the strategies used to control the systems (Wu and Clements-Croome 2007b; Al horr et al. 2016; Alves et al. 2016; Ghaffarianhoseini et al. 2016). In other words, considering the control mechanisms especially those offering practical interaction between indoor/outdoor environment, occupants and facility management team can make a huge difference on the overall performance of building and occupants' well-being. This study revealed that providing a platform and mechanism for interaction of people, including occupants and facility management team, with control approach adopted in building services, including building fabric, facilities and HVAC&R systems, is an essential element of integrated and intelligent design, which should be considered in the decision-making process for HVAC&R systems selection at the early stages of design.

3. Conclusion and needs for further studies

This paper critically reviewed the open literature related to the field of HVAC&R systems selection and identified some of the gaps which need to be addressed in order to develop a comprehensive and robust decision-making process.

Review of the open literature revealed that HVAC&R systems selection process includes the performance evaluation of a few alternatives to choose the most appropriate solution. This process can be significantly influenced by time and knowledge of the designers and relies on their experience and capabilities. In addition, the clients are challenged with the approval of design recommendations and evaluation of the alternative systems considering the decision-making criteria. They have to ensure that the recommended proposal complies with the requirements of the project. However, due to lack of time and knowledge, they are compelled to rely on suitably competent designers' and advisers' recommendations to avoid spending a great deal of time and effort.

The previous studies in this field were categorised into four main groups. For each individual research in each group, the criteria that were considered for decision-making together with the decision-making method and the scope of study were identified. In addition, the advantages and deficiencies associated with each decision-making approach adopted in the reviewed studies are analysed critically.

Based on the critical review of the previous studies conducted in this research, the future models and tools should be able to overcome the deficiencies of the existing models through:

- Considering a broad range of primary and secondary alternative HVAC&R systems together with considering the interaction between these two parts.
- Considering both challenges and opportunities that building/site location can offer. For example, a site may offer opportunities to utilise a water source heat pump with minimal capital cost, or the site may have no main gas supply.
- Considering the reliability and LCC of the systems from cradle to grave, indoor air quality and noise level together with health and well-being and occupants satisfaction.
- Considering strategies for HVAC&R systems control and capabilities to facilitate the interaction between building services and people, including both occupants and facility management team.
- Assisting designers and decision makers and not only researchers.
- Analysing the alternatives based on a reliable source of information.

- Ranking the alternative systems based on a robust and formal decision-making model within a reasonable time.
- Considering the probabilistic changes that are likely to occur in the future, for example, climate change and global warming and decarbonisation of the electricity supply within the context of decision-making process.

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