A Multi-criteria Assessment of HVAC Configurations for Contemporary Heating and Cooling Needs

A multi-criteria assessment of HVAC configurations for contemporary heating and cooling needs

Ilaria Abbà[1[0000-0001-7952-5309]] and Giulia Crespi[1[0000-0001-5087-939X]]

[1] TEBE-IEEM Research Group, Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy
ilaria.abba@polito.it

Abstract. Due to the significant impact that HVAC systems have on the overall building consumption, there is the need to encourage consumers to invest in increasingly more efficient and sustainable technologies to accelerate the transition of the building sector. Moreover, new occupants' habits, higher environmental awareness, and the increment of external air temperatures due to climate change are varying buildings energy demands, which are highly experiencing also simultaneous heating and cooling needs. Consumers' investment decisions in the building sector are usually driven by financial convenience. However, the energy investment decision-making process is a multi-dimensional problem, characterized by different and often conflicting aspects, belonging to energy, technological, financial, environmental, and social domains. In the light of the above, the work aims to compare different electric HVAC configurations, capable of meeting the same contemporary heating and cooling loads, from a multi-perspective standpoint, ranking their performances according to a set of criteria that can potentially influence the choice of the most appropriate HVAC solution in line with consumers' needs. To this purpose, a multi-criteria analysis is developed, in the form of the PROMETHEE II method, with the final scope of ranking the selected alternatives according to different and conflicting criteria.

Keywords: HVAC configurations, contemporary heating and cooling loads, multi-criteria decision analysis.

1 Introduction

It is well known that buildings are among the most environmentally impacting economies at global level, with the HVAC sector playing a crucial role in the attempt of reducing its consumptions and emissions. Indeed, due to the significant impact that HVAC systems have on overall building consumption [1], there is the need to encourage consumers to invest in increasingly more efficient and sustainable technologies to accelerate the transition of the building sector, which will be largely shaped by electrification, identified as a key pillar of this changeover, in line with European trajectories [2]. The investigation on buildings retrofit solutions and efficient HVAC technologies needs to face the changes in buildings energy demand due to new occupants' habits and behaviors (i.e., the diffusion of smart working activities because of the COVID-19 pandemic) and due to climate change and global warming consequences, which are mostly reflected in a severe increment of external air temperatures [3]. All these aspects influence building energy demands, varying typical heating and cooling profiles and increasing air conditioning needs and consumptions. Moreover, all these considerations profoundly affect energy systems reflections, asking for the adoption of more efficient technological solutions, able to satisfy in a cost-effective way also simultaneous heating and cooling requests [4, 5]. Despite the interesting solutions already present in the market to meet new buildings energy needs, in the process of selecting the most appropriate HVAC configurations for a specific building, the comparison is usually done according to their technical or financial performances, assessed separately, without deepening any possible trade-off between the different perspectives [5]. From a consumer standpoint, indeed, decisions are usually made according to a purely financial perspective, selecting the solution to be installed based on financial convenience, rather than on energy or environmental considerations. However, decision-making in the energy field is by definition a multi-dimensional problem, which asks for proper methods to study and rank the alternative solutions at disposal [6]. In this framework, evaluation tools are in the spotlight for supporting the decision-making process, being instruments capable of studying energy issues by integrating different elements, belonging to diverse and often contrasting domains [6]. Among these tools, multi-criteria decision analysis (MCDA) methods are commonly used for supporting investment and design decisions in the building sector, considering the judgements or preferences of the different stakeholders potentially involved in the decision-making process. In line with this, the work aims to compare different HVAC systems, capable of meeting the same contemporary space heating and cooling loads, not focusing on a mere energy comparison between the considered alternative configurations but enlarging the discussion to a multi-perspective standpoint, to consider a richer set of criteria that can potentially influence the choice of the most appropriate HVAC configuration. To this purpose, a multi-criteria analysis is developed, in the form of the PROMETHEE II (Preference Ranking Organization METHod for Enrichment of Evaluations) method, with the final scope of ranking the selected alternatives according to different and conflicting multi-dimensional criteria.

2 Materials and methods

In recent years, dealing with energy issues or energy transition concept has been no longer a mere energy matter, but has increasingly involved environmental, financial, and social aspects [6]. When dealing with complex issues, a MCDA approach allows to consider different and often contrasting standpoints. For this reason, MCDA tools are particularly useful to help decision-makers in expressing rationale and consistent preferences, needed to take confident decisions [7] and are acknowledged as beneficial in providing to interested stakeholders an instrument to select the best strategical option or to rank the studied alternatives, in accordance with their needs and goals [8, 9]. Generally speaking, a typical MCDA follows specific methodological steps: (i) to frame the research context, defining scope, target and key involved stakeholders; (ii) to identify the alternatives to be compared and evaluated; (iii) to define the evaluation criteria;

(iv) to score the performances of each alternative against the criteria; (v) to weight each criterion to reflect its relevance with respect to the others in the decision process; (vi) to combine weights and scores for each alternative to get an overall value; and (vii) to examine results and to perform proper sensitivity analyses to evaluate if and how changes in scores or weights can affect the overall results [7].

Despite the general characteristics of the multi-criteria approach, there exists a variety of MCDA techniques, characterized by different definitions of the decision context, nature of information (e.g., qualitative, quantitative, or mixed), disaggregation of complex problems, level of compensation and weighting technique for estimating the final scores of the considered alternatives. Specifically, for the scope of this research, the outranking PROMETHEE II method was selected [10], allowing to manage, select, and rank a finite set of alternatives according to diverse criteria. In detail, once selected the proper alternatives and criteria for the study, according to the general MCDA framework, the following methodological steps need to be carried out [10]:

1. Establishment of a double-entry impact matrix, connecting alternatives and criteria.
2. Application of a proper preference function to each criterion to identify how much an alternative is preferred to another; each is a normalized function between 0 and 1, where 1 corresponds to a huge preference of an alternative over the other, while 0 means that the decision-maker is indifferent between the two alternatives.
3. Weighting of each criterion, according to experts' preferences, to define its importance with respect to the others in the decision process; the weights assignment allows to calculate the overall preference index for each alternative, which represents the intensity of one alternative over the others.
4. Computation of the outranking flows (i.e., leaving and entering flows) for the different alternatives; the higher the leaving flow and the lower the entering flow, the better the alternative is.
5. Comparison of outranking flows by calculating the net flows between the alternatives to define the complete ranking of the alternatives and to identify the best solution(s).

The weighting process is here performed involving experts with different expertise and background, potentially affected by or influencing the decision-making process; based on each expert's preferences, different scenarios of analysis can be defined. In this work, the Simos-Roy-Figueira method (SRF) was exploited for the experts' involvement [11]. All other steps were performed using the user-friendly Visual PROMETHEE software.

3 Case study

The multi-criteria assessment was performed to compare and rank different HVAC systems, able to meet the same thermal loads, for supporting energy investments decision-making. In recent years, attention is mainly devoted to electric technologies, which deployment in new and retrofitted buildings can guarantee energy efficiency improvements, reduced environmental impacts and energy consumptions [12]. For this reason, in this work, five all-electric HVAC configurations were selected as alternatives, modeling their operation modes using the characteristics of real commercial units. All systems were compared for equal load profiles, defined as Gaussian-shaped curves (see Fig. 1) [4, 5], having fixed an average percentage of contemporaneity of space heating and cooling needs, equal to 52%. Maximum heating and cooling loads were set equal to 640 kW and 630 kW, respectively [5]. The external air temperature distribution of Strasbourg was considered for the analysis.

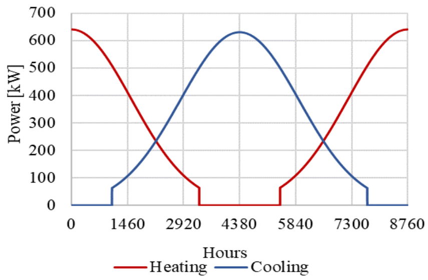

Fig. 1. Gaussian-shaped load profiles for a 52% percentage of contemporaneity [4, 5].

Due to the presence of contemporary heating and cooling requests during the year, different units were coupled in multi-unit systems able to match the required loads; specifically, 4 configurations consider the integration of reversible heat pumps (HPs), electric boilers (EBs) or chillers (CHs) to guarantee the satisfaction of contemporary needs. Conversely, the last configuration is characterized by the presence of a single unit, the polyvalent heat pump (PHP), which is recognized as a promising, but still not widespread solution for buildings [4, 5], able to provide space heating and cooling simultaneously and independently, and not only seasonally, as traditional HPs. From a technical perspective, the PHP can be defined as a heat pump equipped with a heat recovery unit, allowing the machine to operate in three different modes: heating only (as a traditional HP), cooling only (as a traditional chiller) and combined heating and cooling (which represents the main strength of this technology). The considered configurations are summarized in Table 1, dividing them between primary and secondary units and according to the loads they primarily match.

Table 1. Selection of alternatives.

	Primary unit	Secondary unit
HP + EB	Reversible HP (660 kW) with priority on space cooling	Electric boiler (500 kW) as backup for space heating contemporary needs
HP + CH	Reversible HP (660 kW) with priority on space heating	Chiller (520 kW) as backup for space heating contemporary needs
HP + HP	Reversible HP (660 kW) with hourly priority on the highest need	Reversible HP (370 kW) as backup for the non-served contemporary needs
EB + CH	Electric boiler (640 kW) for space heating needs	Chiller (660 kW) for space cooling needs
PHP	Polyvalent heat pump (660 kW) for space heating and cooling needs	

Once alternatives were defined, the following step concerned the identification of the evaluation criteria and the definition of their corresponding preference functions. For the sake of simplicity, criteria were divided into 4 main dimensions (i.e., technical, energy, financial and environmental), as shown in Fig. 2; a total of 10 criteria was considered, being all quantitative, with the sole exception of TECH.2.

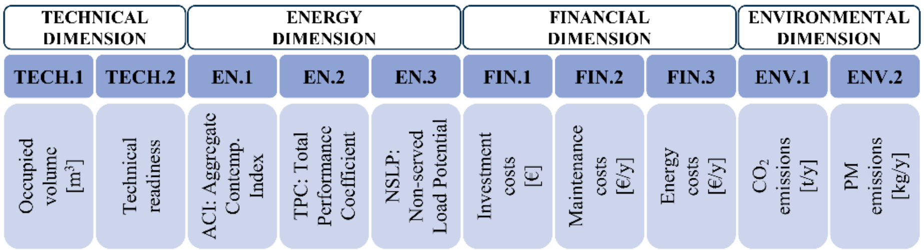

Fig. 2. Set of evaluation criteria.

Going into detail, within the technical dimension, occupied volume (TECH.1) and technical readiness (TECH.2) criteria were identified. TECH.1 is a quantitative criterion evaluating the overall encumbrance (in m^3) of each HVAC configuration, extrapolated from technical datasheets; on the other hand, TECH.2 is a qualitative criterion expressing the level of maturity and deployment of the considered technologies. Concerning the energy dimension, three quantitative criteria were identified and computed using a numerical model, developed in order to couple the considered load profiles with the units operation modes [4, 5]: Aggregate Contemporary Indicator (ACI), Total Performance Coefficient (TPC) and Non-served Load Potential (NSLP). ACI (EN.1) aims to evaluate the units performances only in contemporaneity hours, calculating the ratio between the requested contemporary heating and cooling loads and the corresponding electricity consumption [5]. Conversely, TPC (EN.2) is an annual indicator used to evaluate the total energy performance of the units, computed as the ratio between the sum of all requested loads and the total yearly electricity consumption [4]. Finally, NSLP (EN.3) indicates in percentage terms the quota of contemporary load that the primary unit would not be able to satisfy alone, without integration (NSLP is null for the PHP, meaning that all contemporary loads can be satisfied by the PHP unit) [5]. Moving to the financial dimension, investment (FIN.1), maintenance (FIN.2) and energy (FIN.3) costs were included. For FIN.1 estimation, real investment costs of commercial units were considered, with the sole exception of the cost of the electric boiler, derived from [3]. Annual maintenance costs were computed as percentages of the units investment costs, in line with [13], while energy costs were computed considering non-domestic electricity prices from [14] for the year 2019 (only variable quota was considered). Finally, CO_2 (ENV.1) and PM (ENV.2) emissions were identified as quantitative criteria for the environmental dimension, computed using appropriate emissions factors for electricity [15, 16]. Based on alternatives and criteria definition, the impact matrix can be built by computing, per each alternative, the value of each criterion. Fig. 3 shows the input parameters of the double-entry impact matrix (with alternatives on the rows and criteria on the columns) and the direction of preference, indicating if criteria should be maximized or minimized, according to their definition. At first glance, it is possible to note that there is not a priori dominant alternative.

	TECHNICAL DIMENSION		ENERGY DIMENSION			FINANCIAL DIMENSION			ENVIRONMENTAL DIMENSION	
Criteria	**TECH.1**	**TECH.2**	**EN.1**	**EN.2**	**EN.3**	**FIN.1**	**FIN.2**	**FIN.3**	**ENV.1**	**ENV.2**
Direction of preference	min	max	max	max	min	min	min	min	min	min
Alternatives										
HP + EB	79.6	Good	1.64	2.29	50.4%	186'240	5'282	371'624	874.6	8.6
HP + CH	73.1	Very good	3.91	3.76	49.6%	298'000	8'940	226'991	534.2	5.2
HP + HP	66.9	Very bad	3.95	3.78	27.1%	272'000	8'160	225'882	531.6	5.2
EB + CH	79.6	Average	1.66	1.65	50.0%	142'240	3'962	515'831	1214.0	11.9
PHP	39.8	Average	5.41	4.24	0.0%	210'000	6'300	201'128	473.4	4.6

Fig. 3. Impact matrix input data.

Based on the performed calculations, a proper preference function needs to be assigned to each criterion, choosing among six types of preference functions, differing in terms of shape and threshold values (i.e., preference and indifference thresholds, if present). In the current application, the linear function was applied to EN.1 and EN.2 and to all financial criteria; the U-shape (i.e., quasi criterion) preference function was selected for both environmental criteria and for EN.3, while the V-shape (i.e., criterion with liner preference) was chosen for TECH.1. Finally, the qualitative criterion concerning the technical readiness (TECH.2) was modeled using the level preference function. Afterwards, the weighting procedure was carried out involving and interviewing three experts with different backgrounds and expertise, relevant for the scope of the analysis, allowing to build three different scenarios: (i) an Energy scenario, according to a building physics expert; (ii) an Environmental scenario, based on the opinions of an expert in the sustainability field for industry; and finally (iii) a Financial scenario, accounting for an economic expert's standpoint. Due to the COVID-19 pandemic, experts' interviews were performed using the online DecSpace tool [17].

4 Results and discussion

Before going into the details of the scenarios results, attention should be paid to the outcomes of the experts' interviews, summarized in Fig. 4. The weights, which are inserted as input to the impact matrix, are coherent with the experts' fields; moreover, it is interesting to note that, despite the different experts' areas of belonging, TECH.2 and EN.2 are considered highly relevant for all three experts. After completing the impact matrix, the outranking flows of the different alternatives can be computed using Visual PROMETHEE software, allowing the definition of the final ranking of the considered alternatives per each developed scenario. In the current analysis, the first two positions of the ranking result to be the same according to all three scenarios, as well as the last one. In particular, the best alternative is always the PHP, followed by the HP+CH configuration, while the worst alternative is represented by EB+CH. On the other hand, configurations HP+HP and HP+EB cover the third and fourth positions for the environmental and energy scenarios, while they experience an inversion in the financial scenario.

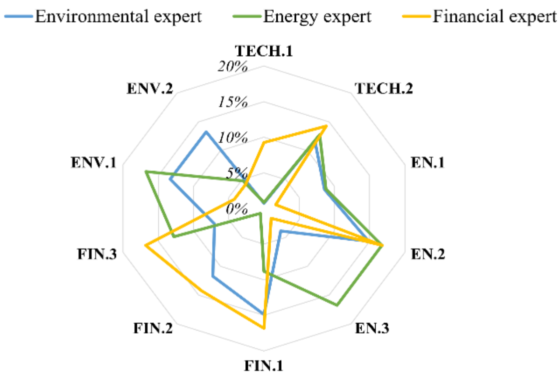

Fig. 4. Normalized weights assigned based on experts' interviews.

To critically analyse results and investigate the impacts of the weighting procedure on the final ranking of the alternatives, a sensitivity analysis was performed by assigning equal weights to all criteria (considering a 10% weight for all 10 criteria). In the Equal Weights scenario, the final rank of alternatives reflects the outcomes of the energy and environmental scenarios; however, the reciprocal distance in terms of outranking flows between the alternatives changes.

Furthermore, starting from this scenario with equal distribution of weights, the robustness of the assessment was addressed by checking the stability range of each criterion. Through Visual PROMETHEE, it is possible to graphically visualize how the alternatives ranking would change because of the variation of the weights assigned to each criterion. In particular, the stability analysis allows to identify the largest range in which a variation of the weight of a criterion does not affect the outcome of the scenario. Table 2 summarises the stability ranges for the Equal Weights scenario, showing the minimum and maximum weights that could be assigned to the different criteria in this scenario to maintain the final ranking of the alternatives unaltered.

Table 2. Stability intervals for the Equal Weights scenario.

Criterion	Min weight [%]	Equal weight [%]	Max weight [%]
TECH.1	0.00	10.00	40.15
TECH.2	3.63	10.00	24.90
EN.1	0.00	10.00	86.09
EN.2	0.00	10.00	98.10
EN.3	0.00	10.00	100.00

FIN.1	0.00	10.00	31.28
FIN.2	0.00	10.00	29.20
FIN.3	0.00	10.00	97.43
ENV.1	0.00	10.00	100.00
ENV.2	0.00	10.00	100.00

EN.3, ENV.1 and ENV.2 criteria experience the greatest stability intervals, while TECH.2, FIN.1 and FIN.2 result to be the most sensitive criteria. For the sake of exemplification, FIN.1 criterion is explored in Fig. 5, in which x- and y- axes represent the normalized weights and the net flow rankings, respectively, while the light blue lines represent the net flow trend of each alternative according to the weight variation. The green/red vertical line is positioned in correspondence of FIN.1 weight in the Equal Weights scenario (10%), while the blue dotted vertical lines represent the minimum and maximum weights for which the final rank of all alternatives remains unaltered. It is interesting to note that if a weight higher than 75% is assigned to FIN.1, the ranking experiences a complete overturning of results, affecting not only the intermediate positions, but also the first and last ones. In particular, if considering a 100% weight for FIN.1 criterion, EB+CH configuration (i.e., the worst in all scenarios) would become the best alternative, having the lowest investment cost. In addition, in this extreme scenario, there is also an inversion of net flow signs for some alternatives.

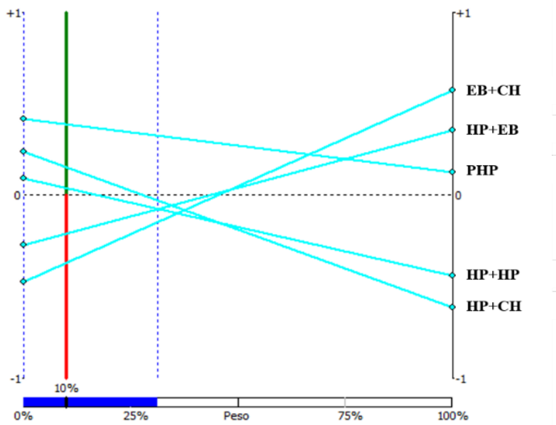

Fig. 5. Stability range for FIN.1 criterion in the Equal Weights scenario.

Based on these considerations on the instability of the financial criteria and bearing in mind that energy investments are usually made by consumers, whose decisions are still mainly driven by the financial convenience of the compared solutions to be installed in their buildings, an additional sensitivity scenario was developed, named Financial Extreme. Specifically, it was built assigning a 25% weight to each criterion belonging to the financial dimension, while the remaining percentage is equally distributed among the other criteria (to guarantee that the sum of all weights is equal to 100%).

Fig. 6 shows a snapshot of the net flow ranking of all five considered scenarios (i.e., Environmental, Energy, Financial, Equal Weights and Financial Extreme). Also in the Financial Extreme scenario, PHP remains the best alternative, even though this scenario induces some relevant variations in the other positions; specifically, it is interesting to note how HP+CH configuration (second-best solution for all other scenarios) reaches the last position in the ranking, while other solutions (and specifically those using the electric boiler) rise, thanks to their lower investment and maintenance costs (e.g., EB+CH and HP+EB), despite their lower environmental and energy performances.

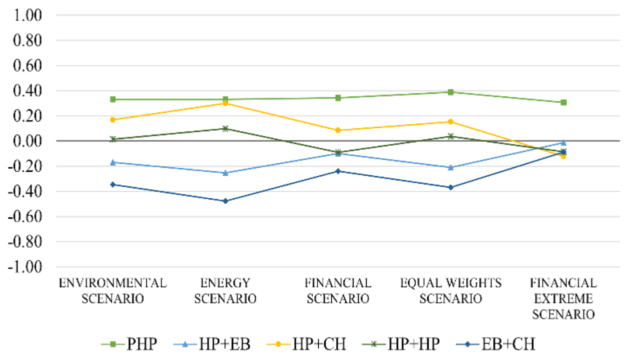

Fig. 6. Final ranking of the HVAC configurations according to the five developed scenarios.

5 Conclusions

The paper presented a multi-criteria assessment, using PROMETHEE II outranking method, to compare and rank different all-electric HVAC configurations, capable of meeting the same contemporary heating and cooling loads, according to diverse experts' preferences. Based on the developed scenarios, for all experts, PHP appeared to be the most promising solution, thanks to its capability of providing heating and cooling services simultaneously and independently. The scenarios results allow to highlight the potentialities of the units from different standpoints and to support consumers' choices in investing on more efficient and sustainable HVAC technologies. Indeed, on the one side, the outcomes can be useful for decision-makers to sustain the evolution of proper financial mechanisms to push consumers' investments; on the other side, technical sales professionals may use the results to support the proposal of still not widespread technologies, such as PHPs, to match consumers' energy needs. Future work will be devoted to enlarging the set of alternatives, including also non-electric technologies, more commonly used in buildings, and to testing other multi-criteria techniques.

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