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Energy and economic assessment of HVAC solutions for the armoury hall at the Palazzo Ducale in Mantua:

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Abstract

Heating, ventilation and air conditioning (HVAC) of historical buildings dedicated to public use as churches, theatres and ancient palaces employed as a museum, implies a number of critical issues, as most historic buildings were not designed to be heated, cooled and ventilated. In this context, the present work represents the assessment of the energy and economic impact of different strategies for the musealization of the armoury hall of Palazzo Ducale, in Mantua. The aim of the study is to provide a preliminary technical-economic definition of the HVAC system which fit the climate characteristics, the building use profile, guaranteeing reversibility of the system and comfort conditions for users, ensuring at the same time a low energy consumption and a high speed of response to changes in thermal load. An analysis of the local climatic parameters together with the simulated building energy demand, allowed the definition of the main requirements and performance for the preliminary sizing of the HVAC system. Different configurations are proposed, according to best available technologies, including novel technologies relying on renewable energy sources. A comparative analysis of the different configurations with respect to the criteria of ease of maintenance, speed of response of the system, noise, size and adjustment of the system, is presented in order to identify the advantages and any disadvantages of the proposed HVAC systems.

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Keywords: historical buildings; friendly heating; sustainable heating; building energy modelling; water-source heat pump; HVAC system

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1. Introduction

In Europe, the building sector is responsible for over 36% of total energy consumption and around a third of greenhouse gas emissions, according to IEA (2018). The majority of such buildings are pre-1990 and a quarter of the existing building stock is composed of historical buildings, as indicated by Buda and Mauri (2019).

Nomenclature

AHU	Air Handling Unit
GW	Groundwater withdrawal/rejection wells
GHX	Geothermal heat exchangers
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
VAV	Variable Air Volume

New buildings reached a considerable improvement toward the nearly Zero Energy Building (nZEB) standards thanks to the European regulatory framework, in particular Directive 2002/91 and Directive 2010/31. On the contrary existing and historical buildings still have very high energy consumption. The problem of relatively low indoor comfort conditions for occupants and in some cases with unacceptable indoor environmental conditions for the conservation of their artworks were stressed by Pigliautile et al. (2019). According to Irati et al. (2016), around 110 million of the existing building require deep renovation. These particular buildings need tailored and feasible solutions, through retrofit interventions which take into account the architectural constraints and the historic physical integrity of the cultural heritage, as described in the CEN standard (2017).

In such framework, a topic increasingly addressed in the literature during the last decade is related to the heating of historical buildings characterized by very huge air volumes and high thermal mass, as churches, which implies a significant thermal power and energy demand for heating. Among them, the most adopted solutions are represented by all-air system, the infrared heaters and the pew-based heating (Aste et al. (2017)). While the first two solutions implies high energy consumption and drawbacks related to the preservation constrains, as underlined respectively by Aste et al. (2016) and Camuffo (2006), the last one seems to be the most innovative one. Pew-based heating system were firstly investigated by Camuffo et al. (2010) as a novel technical solution for local thermal comfort. The authors demonstrated that integrating electric heating foil properly installed as under-seat, under-kneeler and hand-warmer elements can ensure optimal comfort level while minimizing the negative influence on the church and its artworks. Neilen et al. (2004) obtained significant energy savings can be obtained, typically higher than 70% in comparison with on-demand all-air systems. Other advanced solutions for the thermal needs of historical buildings are reported in the literature, as the combination of a water-condensed heat pump (HP), demand-controlled ventilation and trigeneration system presented by Schibuola et al. (2018), respecting preservation orders and constraints defined by authorities.

In such a scenario, the present work represents the prosecution of previous research presented by Leonforte et al. (2019) and is carried out on the same case-study, the Armoury hall at the Palazzo Ducale in Mantua. The assessment of the energy and economic impact of different HVAC solutions for the musealization of the armoury hall is presented, providing guidelines of intervention for the present and also analogous cases.

2. Case study and method

The space object of the retrofit intervention is the armoury hall of the Palazzo del Capitano, built in the 13th century, which is part of the museum complex of the Palazzo Ducale in Mantua. The armoury hall is a single rectangular space that covers an area of about 1000 m^2 (66x15m) with a maximum height of 11m, for a total volume of around 9700m^3. External walls are made by solid bricks and their thickness varies from 70 to 80 cm. The floor and the roof are realized with wooden structures. Thirteen double lancet windows, composed of single glasses and wooden frames, illuminate the indoor space. Currently, the armoury hall is empty, and no system for HVAC is installed. In 2018 the restoration project of the hall has been planned to make this space available for art exhibitions and cultural events. The musealization of the armoury hall indeed requires an interior refurbishment and the installation of a heating and cooling system to ensure the users' comfort and materials preservation.

For such reason, a detailed annual acquisition campaign of the main thermo-hygrometric parameters of the armoury hall, in the current situation, has been carried out and presented by Leonforte et al. (2019). The assessment of the microclimatic parameters supported the realization, the calibration and validation of a virtual model, able to reproduce a realistic building behaviour. Once the building energy model has been validated, the thermal energy demand of the building for its new destination use was estimated through dynamic energy simulations. Heating and cooling energy demand were indeed estimated according to the foreseen activities in the refurbished armoury hall.

According to a deep retrofit planning, considering the climatic condition of Mantua (2786 heating degree day - 316 cooling degree day) the installation of a heating/cooling system to ensure acceptable thermal comfort during the whole year was studied and different intervention strategies were analysed based on dynamic energy simulation results. Three HVAC system solutions aimed at improving the comfort conditions of users and reducing the risk of material degradation has been described and analysed from a technical and economic point of view.

3. Building energy modelling and dynamic simulations

The building energy model of only the portion which includes the armoury hall has been implemented with EnergyPlus software (Fig. 1). The building geometry has been shaped from the architectural drawings and documents collected while thermal properties of the construction materials were selected from CEN standards (2007), UNI-10351 (1994) and literature. In detail, the conductivity and the density of the walls made by brick had been defined considering a pre-industrial brick (XIII-XVIII Centuries) indicated by Akkurt et al. (2020), while the thermal properties of single-glazed windows were selected according to the work presented by Milone et al. (2015) and Coelho et al. (2018). The calculated U-values of the envelope opaque components range between 0.57 and 0.95 W/m^{2}K, while for the windows is 5.8 W/m^2 with a solar heat gain coefficient of 0.8.

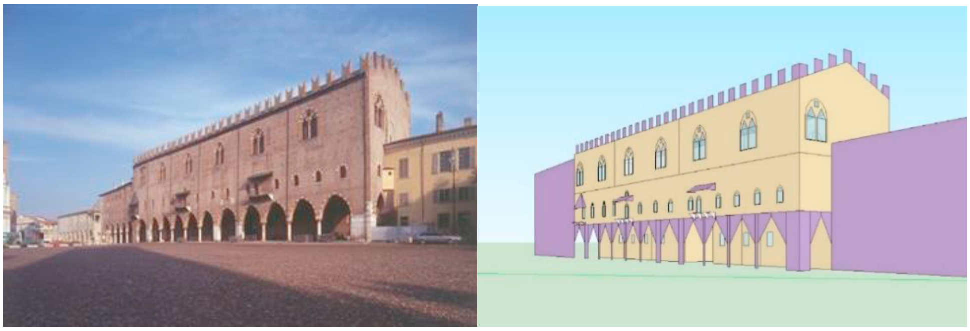

Fig. 1. View of Palazzo Ducale from Piazza Sordello (left) and 3D model (right).

The model calibration was carried out manually through the comparison of simulated and measured annual data of temperature and mixing ratio for the period from August 2017 to July 2018. Detailed results are reported in a previous work presented by Leonforte et al. (2019). The accuracy of the virtual model was assessed mainly through the calculation of the root mean square error (RMSE), that resulted around 1.0°C for indoor temperature and 0.8 g/kg for mixing ratio, and the coefficient of determination (R^2), respectively equal to 0.98 and 0.95. In line with values recommended by the ASHRAE guideline 14 (2002) and the Efficiency Valuation Organization (2012).

The validated building energy model has been used to properly design the HVAC system. In such respect, two different simulations have been performed according to the boundary conditions reported in Table 1:

A) the first, to define the peak heating and cooling power, under worst possible operating conditions;

B) the second, to forecast the annual heating and cooling energy demand, under expected operating conditions;

The ACH was calculated according to UNI-10339 (1995) during opening hours (8–19), while equal to infiltration rate during the night. The heating and cooling peak power (Simulation A) were calculated assuming the upper and lower limit of setpoint temperature, allowed by the law. A high people occupancy was considered in summer, simulating the saturation of the armoury hall during crowded events, while no people occupancy in winter, as this parameter affect the internal gain. Average annual heating and cooling demand (Simulation B) were calculated considering 50 visitors per hours, as foreseen by the Palazzo Ducale administrations, while heating and cooling setpoint were set to reasonable values.

Table 1: Assumptions made in the dynamic energy analysis.

Simulation parameter	Simulation A		Simulation B
	Winter	Summer	All the year
Building's usage profile:	Opening hours from 8 to 19 every day.		
Heating period	From 15 October to 15 April (180 days)		
Heating set-point air temperature	22 °C	-	20 °C
Cooling set-point air temperature	-	24 °C	26 °C
Occupancy	0 people	100 people	50 people
Internal electric loads	0 W/m^2	4 W/m^2	4 W/m^2
Air Change Rate (ACH)	0.15 vol/h	0.3 vol/h	0.15 vol/h

According to the results of simulation A, the maximum thermal power in the design day conditions resulted equal to approximately 70 kW, indeed each HVAC configurations is sized on that peak thermal power. Simulation B was instead carried out to foresee the thermal energy demand of the building during a typical year. Energy demand of 107 MWh/year and 66.4 MWh/year resulted respectively for heating and cooling, corresponding to approximately 108 kWh/m^2 per year and 65 kWh/m^2 per year. Through these results, in the following sections, the energy performance of three different heating/cooling strategies will be evaluated, discussing their integration in the armoury hall and the global cost of each solution.

4. Technical description of the heating/cooling strategies and calculation of the investment cost

In the present section, the different heating/cooling strategies that were considered feasible for the specific application, are described under the technical point of view. For each scenario, the electrical consumption and the total primary energy demand was calculated considering specific technical systems features, daytime operation and assumptions, as described in each section. All the solutions involve the use of water-condensed heat pump (HP) generation systems using groundwater or geothermal wells. At present, the water-source heat pump can be considered the best available technology on the market for heating and cooling in buildings, as its performance is marginally affected by climatic conditions (e.g. the ambient air temperature). The three proposed systems described in the following sub-sections.

4.1. All-air system

The all-air system for heating and cooling consists of a water-source HP, the air handling unit (AHU) and a Variable Air Volume (VAV) distribution and emission subsystem. In detail, the HP provide hot and cold water to the AHU and heat distribution/emission subsystems which are regulated in order to optimally control the air-conditioned area occupied by visitors. In this way, air conditioning consumption are reduced, and alterations of microclimatic conditions can be minimized, preserving the state of conservation of the existing wooden structures.

The water supply is guaranteed by withdrawal/rejection groundwater wells (GW), or alternatively a system of vertical geothermal heat exchangers (GHX). The heat distribution/emission and air treatment system indeed consist of the following main elements:

- AHU with rated airflow equal to 9000 m^3/h of which 6000 m^3/h maximum for recirculation for heating/cooling, humidification/dehumidification and filtration of the supply air in the room.
- All-air distribution and emission system of the VAV type in all areas of the armoury hall.

The annual electricity demand adopting the all-air system resulted equal to 66 MWh/year and was calculated considering an overall efficiency for distribution, regulation and emission systems equal to 85%, heat pump COP calculated on forecasted operating temperatures and rated electric power of auxiliaries equal to 6 kW. The total primary energy demand resulted equal to 142 MWh/year, considering a primary energy conversion factor equal to 2.16 as reported by the Italian electricity and as authority (2008).

4.2. Radiant system and primary air

The second configuration consists of a hydronic radiant system coupled with an air-based system for air renovation. The airflow rate is adjusted to provide only the required air exchange, with thermally neutral characteristics compared to the ambient set-point. The sensible thermal load is provided through a radiant floor heating system. In this sense, lightweight modular elements can be adopted, being weakly inertial and allowing therefore for more rapid operations than traditional radiant elements. This solution is, therefore, able to satisfy the demand for local comfort without significantly altering the internal thermo-hygrometric conditions. The low operative temperature of the radiant terminals allows maximising the conversion efficiency of the water-source HP which is connected to the hot and cold batteries of the AHU. The latter, unlike the first configuration, has a smaller size, i.e. 6000 m^3/h total and is equipped with recirculation to ensure hygrometric control of the room. As in the previous case, both groundwater and geothermal probes can be adopted for water supply to the HP.

This HVAC solution constitutes a mixed type system with both hydronic and aeraulic terminals which are able to meet both winter and summer needs. This system indeed guarantees adequate air renovation according to the actual occupation and metabolic activity carried out, as well as high levels of comfort and pollutant control.

The annual electricity demand adopting the mixed radiant and primary air system resulted equal to 45 MWh/year and was calculated considering an overall efficiency for distribution, regulation and emission systems equal to 87%, heat pump COP calculated on forecasted operating temperatures and rated electric power of auxiliaries equal to 6 kW. The total primary energy demand resulted equal to 98 MWh/year.

4.3. Delocalized water/air heat pump terminals

The proposed configuration consists of the use of delocalized water/air heat pump terminals, connected to a hydronic loop which is indirectly fed by groundwater or by a closed water circuit of geothermal probes. Those heat pump systems cover sensible and latent energy demand, while two air exchange units each of 3000 m^3/h with localized heat recovery (HR) are responsible for the fresh air supply.

In detail, 15 heat pump terminals of approximatively 5 kW of nominal thermal power are expected to be installed. These units are positioned in the thickness of the floor. Emission terminals will be water condensed and connected to a hydronic ring fed by water from groundwater wells or vertical geothermal probes, being also able to operate in free-cooling, as conventional fan-coil units. Finally, flow temperatures of the individual air conditioning terminals can regulate according to the boundary conditions. This solution is characterized by very low invasiveness, allowing for the control of heating/cooling load and humidity according to the needs, while containing energy consumption.

The annual electricity demand adopting delocalized water/air heat pumps resulted equal to 42 MWh/year and was calculated considering an overall efficiency for distribution, regulation and emission systems equal to 84%, heat pump COP calculated on forecasted operating temperatures and rated electric power of auxiliaries equal to 3 kW. The total primary energy demand resulted equal to 91 MWh/year.

5. Global-cost analysis

A cost-analysis was carried out in order to evaluate the cost-effectiveness of each proposed solution. The global cost (C_G) during a reference lifetime was calculated accounting the initial investment cost and the annual operation

$$C_G(t)=C_I+\sum_{i=1}^{t}\frac{C_{a,i}}{(1+r)^i}-V_{f,t}$$

costs, by means of a present worth analysis to construct the cumulative cash flow (year by year). The GC was calculated according to the following formula indicated in CEN standards (2008):

Where C_I is the initial investment cost, as calculated in Table 1Table 2 (€); $C_{a,i}$ is the annual running cost during each year *(i),* considering the energy cost (electricity and/or natural gas) and the maintenance cost (€); t is the length of the calculation period (years); r is the real interest rate (-); $V_{f,t}$ is the residual value of the components at the end of the calculation period (€).

Every single item of the HVAC system was derived from reference price-lists for public works reported by the Milan Municipality (2019) and verified, where feasible, with average literature values. In Table 2 the total cost of investment of each HVAC solution is indicated, for both systems with groundwater wells (GW) or alternatively, geothermal heat exchangers (GHX). As well, the amount of the main cost voices is reported: heat pump (HP), air handling unit (AHU), management & control system (MCS), electric system (ES) and water storage (WS).

Table 2: Investment cost of each HVAC solution.

HVAC system	Source	Generation	Distribution	Emission	Other	Total cost
All-air system	GW: 25’000 €	HP: 25’000 €	Hydraulic: 13’000 €	10’000 €	MCS: 48’000 €	GW: 188’500 €
	GHX: 70’000 €	AHU: 20’000 €	Aeraulic: 25’000 €		ES: 20’000 €	GHX: 233’500 €
					WS: 2’500 €	
Radiant system and primary air	GW: 25’000 €	HP: 25’000 €	Hydraulic: 13’000 €	40’000 €	MCS: 40’000 €	GW: 200’500 €
	GHX: 70’000 €	AHU: 15’000 €	Aeraulic: 20’000 €		ES: 20’000 €	GHX: 244’500 €
					WS: 2’500 €	
Delocalized water/air heat pump terminals	GW: 20’000 €	HP: 40’000 €	Hydraulic: 6’000 €	5’000 €	MCS: 40’000 €	GW: 161’000 €
	GHX: 50’000 €	HR: 15’000 €	Aeraulic: 15’000 €		ES: 20’000 €	GHX: 191’000 €

The estimation of the annual running cost $C_{a,i}$ was calculated from the total annual demand of electricity for each solution, calculated on the basis of total energy demand and system conversion efficiency in every operative condition. Furthermore, the prices of electricity were derived considering the mean tariffs in Europe for the household sector, provided by Eurostat (2019). The average maintenance cost and the expected lifetime for each main component (e.g. hot-air generator, heat pump, etc.) were instead considered as a percentage of the investment cost, according to the values reported in the EN-15459 (2008) and summarized below.

Table 3: Maintenance cost of each HVAC system components.

Main component	Average Lifespan	Average annual maintenance in % of the initial investment
Air conditioning units	15	4
Water floor heating	50	2
Heat pumps	17.5	3
Control system & equipment	20	3
Fans with variable flow	15	6
Air ducts and diffuser	30	2
Pipes/wires	40	1

The reference calculation period was set equal to 30 years, which is a reasonable value commonly used for cost-optimal assessments of technical systems and energy-saving measures. Consequently, considering the above-reported average lifespans, the replacement cost was accounted when necessary. To simplify the evaluation, the residual value of the components at the end of the calculation period $V_{f,t}$ is supposed to be equal to 0 in all cases. The global cost C_G was, therefore, obtained adding up the initial investment cost C_I and the annual running cost $C_{a,i}$ actualized for each year of the calculation period. The other fundamental assumptions for the calculation of the actualized $C_{a,i}$ are summarized in the following table.

Table 4: Reference parameters for the economic analysis.

Parameter	Unit	Value
Electricity cost	€/MWh	20
Rate of annual increase of O&M costs	%	2.0
Real investment rate (r)	%	3.0

The global cost $C_{G(30)}$ for each HVAC solution is thus reported in Fig. 2, divided among investment and running costs, including all expenses for operations and maintenances. The costs of the three HVAC solutions are reported considering the use of two different heat sources: groundwater (GW) or geothermal heat exchangers (GHX).

It can be observed from reported results, that the use of groundwater is cheaper than employing geothermal heat exchanger and should be always preferable where groundwater is abundant and available as energy source, as in Po Valley where Mantua is located. The investment cost is higher for the mixed water-air solution due to the high cost of the radiant floor for such a large space. The all-air solution is cheaper, while the delocalized HP solution allows the lower investment cost, as smaller hydraulic distribution is needed and no AHU units is present.

The incidence of running expenditures on the final global cost is considerably high for the all-air and delocalized HPs solution. On the contrary, the mixed water-air solution has lower running costs. The reason for higher all-air O&M costs is due to the large aeraulic distributing system, which leads to larger electricity and maintenance costs. The delocalized HP system present higher O&M costs due to a large number of HP terminals. Those HP units do not take advantage of the scale effect that a centralized HP allows in terms of performances. Moreover, having many HP terminals means requiring for more frequent maintenance, with related human-labour costs.

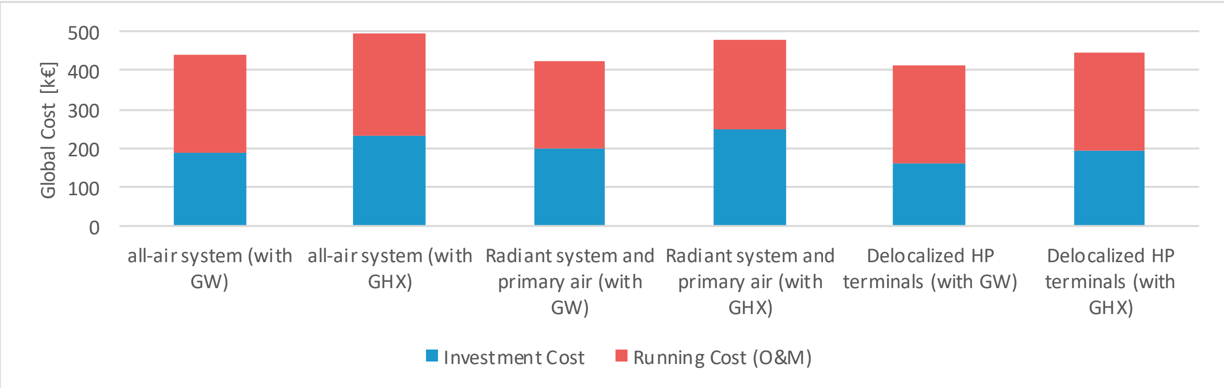

Fig. 2. Global cost (spilt in investment and running costs) for each HVAC solution over a 30-years calculation period.

6. Conclusions

The present work represents the assessment of the energy and economic impact of different strategies for a historical building in Mantua. The delocalized systems is the most cost-effective in terms of global cost on a reference period of 30 years. However, fan operation and airflow typically produce noise and are characterized by higher maintenance costs, being indeed convenient for sporadically used spaces. On the contrary, the all-air system is characterized by ducting and grilles that are invasive from an aesthetic point of view for the historic buildings. The radiant system and primary air solution is characterized by the similar global cost of the previous configurations, but higher investment cost, savings in operating costs, thus becoming convenient for frequently used spaces. The radiant floor system, coupled with an air exchange system, is also able to guarantee a high level of comfort, low stratification effect and low noise impact with respect to the other solutions.

From the responsiveness point of view, the all-air system is preferable if the heating space is characterized by a high number of people at the same time, but not continuously during the period of operation. On the contrary, the mixed water-air solution can generally be considered inertial and therefore suitable if there is a continuous use of space during the day. This type of system is also ideal if a low density of people is expected. The solution with delocalized HP has a high response speed, comparable to an all-air system. Moreover, it has the advantage of a low power consumption at partial loads, since it is possible to operate a small number of terminal units at a time.

According to the characteristics and requirements of the intervention, the solution with radiant floor and primary air change is the most appropriate for this specific case study. The armoury hall is expected to be used every day from 8 a.m. to 7 p.m., requiring for continuous air conditioning, even during the night to avoid thermal stress the historical structures and artworks. In addition, this solution ensures adequate thermal and acoustic comfort for the quite large number of expected users.

In general, HVAC systems for historic buildings need careful analysis in terms of cost, performance and comfort. A detailed assessment should be carried out by practitioners and experts, considering the many constraints imposed on historic buildings and the unique characteristics of each context where the intervention is carried out.

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