Parametric Technical and Economic Analysis of Thermal Comfort and Productivity in Industrial Buildings

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Abstract

Thermal comfort is an important aspect to occupants' well-being and productivity in a workplace. Indeed, as observed by some authors in the literature, a high thermal comfort can improve workers' productivity and progressively reduce the number of accidents as well as occupational diseases. This paper aims at investigating to what extent the level of thermal comfort in workplace influences productivity, estimated according to Roelofsen model (2001). In particular, the study analyses the economic benefits of investing in additional air-conditioning systems to improve thermal comfort conditions, considering the impact of insulation of the envelope, internal gains and climate.

1. Introduction

In workplaces, the indoor environment quality - IEQ has an impact not only on people's comfort, health and safety but also on their productivity (Haynes, 2008). Moreover, in industrialized countries, labour costs often exceed energy costs (Wood, 1989). Although higher productivity rates can be key factors for economic success, limited interest is generally given to indoor comfort conditions in productive buildings and the focus is only on energy aspects.

The literature reports several studies describing the relationship between occupants' comfort conditions, health and productivity in workplaces (Milton et al., 2000; Wyon et al., 2000). In a previous research (Tarantini et al., 2017), the authors focused on a specific IEQ aspect, i.e., thermal comfort, and reviewed the literature about its correlation with performance and productivity, observing that several researches report losses due to thermal discomfort conditions. For example, Wyon and Wargocki (2005) underlined that some air temperature conditions can lower arousal and learning performance (Wargocki and Wyon, 2006), reduce manual dexterity and increase Sick Building Syndrome symptoms. Lan and Lian (2009) reported productivity loss when workers are in non-neutral comfort conditions, especially when feeling warm (Lan et al., 2011). DeRango (2003) observed that neutral thermal comfort conditions lead to a reduction of physical efforts and a growth of productivity. However, as observed by the authors (Tarantini et al., 2017), only a limited number of models are available for a quantitative assessment of productivity changes as a function of thermal comfort conditions. One example is Roelofsen model (2001).

This paper analyses the economic convenience of the adoption of HVAC solutions to ensure thermal comfort conditions in productive buildings. A small-size productive building of 1500 m^3 was modelled with TRNSYS and a sample of 30 different configurations defined, from a full factorial combination of five European climates, two levels of internal gains and three different kinds of opaque components. The parametric set was simulated considering two scenarios - with or without sensible cooling system, and, for both, the productivity in each working hour was assessed by means of Roelofsen model (2001). Afterwards, the net present value, NPV, was calculated for each configuration without mechanical cooling, considering the installation cost of the sensible cooling system, and the running costs related to the energy and workforce.

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2. Methods

2.1 Set of Configurations

A small productive building of 30 m x 10 m x 5 m, with façades oriented towards the main cardinal directions, was selected as the base case to build a parametric set of configurations and modelled with TRNSYS 17 (SEL, 2012) as a simplified mixed thermal zone. South and north façades have a window area of 4.32 m^2 and a door area of 14.4 m^2 each. East and west façades have, respectively, window areas of 34.56 and 26.4 m^2 and the latter includes also a door of 22 m^2.

Windows have a glazing thermal transmittance U_{gl} equal to 2.83 W m^{-2} K^{-1}, a SHGC of 0.755, no shadings and a frame thermal transmittance U_{fr} equal to 3.2 W m^{-2} K^{-1}, while doors have a thermal transmittance of 1.4 W m^{-2} K^{-1}. As summarized in Table 1, three different wall constructions (i.e., concrete wall, concrete wall with an external insulation and sandwich wall - respectively “concrete”, “ins_conc” and “sandwich” in the next Figures and Tables) were considered. Taking into account the different surfaces finishing, a solar absorbance of 0.3 was assumed for the two concrete walls and 0.6 for the sandwich wall. The three types of envelope were selected in order to cover a wide range of components, from the uninsulated ones, common in South Europe, to insulated and well-insulated ones, more frequent in North Europe. The typical weekday work schedule was assumed from 8:00 am to 5:00 pm, including the break hours, and no-work was programmed over the week-end. A total of 30 workers were considered.

Table 1 – Envelope details of the 3 kinds of opaque components, with materials properties according to the UNI EN ISO 10456 (UNI, 2008)

	Layer	Thickness [m]	Thermal Conductivity [W m^{-1} K^{-1}]	Specific Heat Capacity [kJ kg^{-1} K^{-1}]	Density [kg m^{-3}]
CONCRETE WALL (“concrete” in the Figures)					
Ground floor [U = 4.17 W m^{-2} K^{-1}]	Concrete slab	0.08	1.15	1	1800
External wall [U = 2.91 W m^{-2} K^{-1}]	Concrete block	0.20	1.15	1	1800
External roof [U = 0.44 W m^{-2} K^{-1}]	Concrete block Polystyrene	0.10 0.08	1.15 0.04	1 1.47	1800 40
INSULATED CONCRETE WALL (“ins_conc” in the Figures)					
Ground floor [U = 4.17 W m^{-2} K^{-1}]	Concrete slab	0.08	1.15	1	1800
External wall [U = 0.41 W m^{-2} K^{-1}]	External plaster Polystyrene Concrete block	0.03 0.08 0.20	0.43 0.04 1.15	1 1.47 1	1200 40 1800
External roof [U = 0.44 W m^{-2} K^{-1}]	Concrete block Polystyrene	0.10 0.08	1.15 0.04	1 1.47	1800 40
SANWICH WALL (“sandwich” in the Figures)					
Ground floor [U = 4.17 W m^{-2} K^{-1}]	Concrete slab	0.08	1.15	1	1800
External wall [U = 0.11 W m^{-2} K^{-1}]	Zinc corrugated sheet Polystyrene Zinc corrugated sheet	0.002 0.35 0.002	30 0.04 30	0.460 1.47 0.460	7900 40 7900
External roof [U = 0.32 W m^{-2} K^{-1}]	Zinc corrugated sheet Polystyrene Zinc corrugated sheet	0.002 0.12 0.002	30 0.04 30	0.460 1.47 0.460	7900 40 7900

During occupancy hours, a natural ventilation rate of 30 $m^3 h^{-1}$ per person was imposed in accordance with EN 13789 (CEN, 2007a). An infiltration rate of 0.07 vol h^{-1} was estimated in accordance with EN 15242 (CEN, 2007b) and UNI EN 12831 (UNI, 2006), considering a leakage rate at 50 Pa of 5 $m^3 \cdot h^{-1}$ per m^2 of façade and a shielding coefficient of 0.03. Two levels of internal sensible gains, i.e., 20 $W \cdot m^{-2}$ and 40 $W \cdot m^{-2}$ (respectively "_20" and "_40" in the next Figures and Tables), were considered as representative of different type of activity sectors according to DIN V 18599 1-10 (DIN, 2016), with a total of 6000 W or 12000 W, half convective and half radiative as suggested by EN ISO 13790 (CEN, 2008). In line with the ISO 7730 (ISO, 2005) metabolic rate of 1.6 met (i.e., light industry activity) and with ASHRAE Handbook of Fundamentals (2009), internal gains per occupant were set to 75 W of sensible heat, 43.5 W radiative and 31.5 W convective, and 158 $g \cdot h^{-1}$ of generated water vapour. Considering the presence of 30 occupants, the building was characterized by additional 2250 W of sensible gains. The analysis was performed considering five European climates: Berlin, Germany, Messina, Milan and Rome, Italy, and Vienna, Austria. TMY2 weather data were used as weather data source. A seasonal distinction, with summer lasting from June to September or from May to October, depending on the weather data of each location, was applied for the clothing factor, with 1 clo for winter and 0.5 clo for summer time according to ISO 9920 (ISO, 2007).

Every case was simulated with an ideal sensible heating system with an air temperature setpoint of 18 °C according to the Italian law, DPR 412 (President of the Italian Republic, 1993). The heating system starts running an hour before the set working timetable (i.e., 7:00 am) and turns off at the end of the working timetable (i.e., 5:00 pm). The set of 30 cases was modelled both with and without sensible cooling system. For those configurations with sensible cooling system, it was modelled as an ideal system with an air temperature setpoint of 26 °C, operating during occupancy time. Heating and cooling systems are operative all year long, without a definition of heating and cooling seasons.

2.2 The Estimation of the Productivity Loss

As explained in the introduction, in this work Roelofsen model (2001) was used to calculate the productivity losses due to non-neutral thermal comfort conditions. The model was developed for office environments and, in the current research, was applied considering specific working tasks, such as assembly work, manufacturing machine programming and quality control, which are comparable to office tasks in terms of mental activities. The model estimates the percentage of hourly productivity loss as a function of Fanger's Predicted Mean Vote, PMV, distinguishing thermal discomfort by cold and warm sensation (Fig. 1 and Table 2).

$$PL = b_0 + b_1 \cdot PMV + b_2 \cdot PMV^2 + b_3 \cdot PMV^3 + b_4 \cdot PMV^4 + b_5 \cdot PMV^5 + b_6 \cdot PMV^6 \qquad (1)$$

Productivity loss was neglected in case of a slightly cold sensation, i.e., in a range of PMV between 0 and -0.5 (see Fig. 1). Moreover, Jin et al. (2012) suggested a limit of applicability for the Roelofsen model, equal to $-1.4 \le PMV \le +1.5$. In this study, the productivity losses found for PMV = -1.4 and for PMV = +1.5 were adopted also for smaller and larger PMV, respectively.

Table 2 – The values of the regression coefficients, b0 - b6, in Equation (1)

Regression coefficients	PMV < 0	PMV > 0
b0	1.2802070	-0.15397397
b1	15.9954510	3.88202970
b2	31.5074020	25.17644700
b3	11.7549370	-26.64136600
b4	1.4737526	13.11012000
b5	-	-3.12968540
b6	-	0.29260920

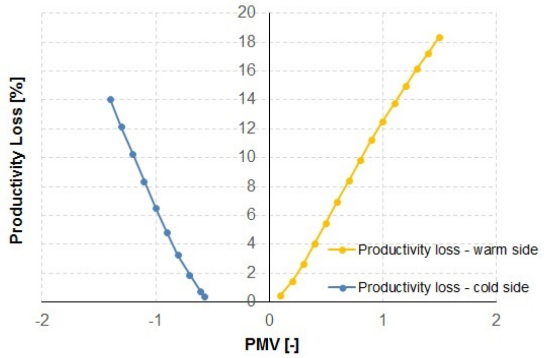

Fig. 1 – Productivity loss according to Roelofsen model (2001)

2.3 Economic Analysis

For each case not equipped with cooling, the Net Present Value, NPV, was calculated, according to the following assumptions:

- investment costs of a cooling system in the range of 11 200 EUR to 17 000 EUR, depending on the required capacity, sizing from 5 kW to 20 kW and selected to satisfy only sensible cooling; indeed, considering the significant air change rate per ventilation and infiltration, the impact of internal vapour generation was assumed limited.
- running electricity costs according to Eurostat data, respectively equal to 0.1979 EUR kWh_{el}^{-1} (Austria), 0.2804 EUR kWh_{el}^{-1} (Germany) and 0.3229 EUR kWh_{el}^{-1} (Italy);
- labour hourly costs according to Eurostat data, respectively equal to 34.9 EUR h^{-1} per worker (Austria), 37.1 EUR h^{-1} per worker (Germany) and 28 EUR h^{-1} per worker (Italy);
- real discount rate of 3 % and period of consideration of 20 years;
- seasonal Coefficient of Performance, sCOP, of the cooling system equal to 3.5, selected to comply with the minimum requirements by the Italian law (Italian Government, 2015).

Moreover, an economic sensitivity analysis was performed on the number of workers, accounting also for the scenarios with 20 and 40 workers in addition to the reference case with 30.

3. Results

3.1 Annual Energy Demand

The specific annual energy demand for heating and cooling were analysed for each configuration. Heating demand ranges from the minimum in Messina to the maximum in Berlin, respectively for the insulated cases with high internal gains (less than 1 kWh m^{-2} a^{-1}) and for the uninsulated cases with low internal gains (more than 50 kWh m^{-2} a^{-1}), as it can be seen in Fig. 2. On the contrary, the opposite is true for the cooling needs, with the largest demand in Messina for the case with sandwich walls and high internal gains (more than 30 kWh m^{-2} a^{-1}) and almost null demand in Berlin and Vienna for the cases with concrete components and low internal gains (Fig. 3).

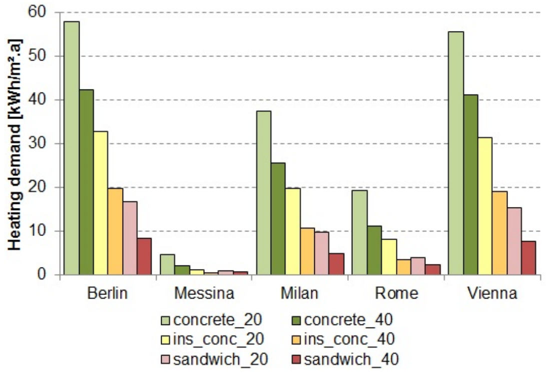

Fig. 2 – Comparison of the annual heating demand for the simulated configurations

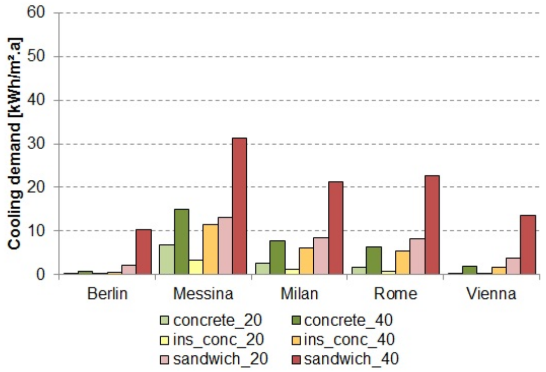

Fig. 3 – Comparison of the annual cooling demand for the simulated configurations with cooling system

3.2 Operative Temperature

The annual distribution of the hourly operative temperatures simulated during the working hours was represented by means of box and whisker charts. For each of the analysed cases, the upper lines represent the maximum, the lower lines the minimum, the points in the middle the medians and the rectangular boxes the range between the first and the third quartile of all the operative temperatures in the simulated working hours.

Focusing on the interquartile ranges of the distributions, it can be seen that the solutions with low internal gains show operative temperature values lower than the ones with high internal gain. The same is true for those cases with uninsulated components with respect to those with insulated or well-insulated envelope, and moving from colder to warmer climates. The result of the installation of a cooling system is clearly visible by comparing Fig.s 4 and 5. As it can be seen in the latter Figure, the cooling system is able to keep the maximum values of the operative temperature below 27 °C during occupancy time, with the largest benefits registered for the city of Messina, especially for the solution with the sandwich wall and high internal gains.

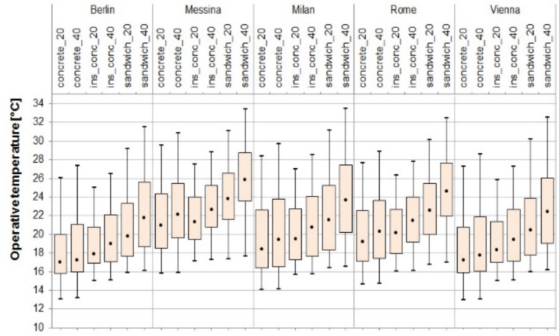

Fig. 4 – Distributions of hourly operative temperature for the cases without cooling system, during working hours

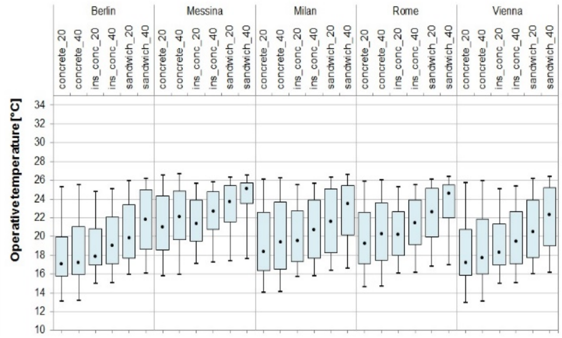

Fig. 5 – Distributions of hourly operative temperature for the cases with cooling system, during working hours

3.3 Annual Distributions of PMV and PPD

The PMV annual distributions were calculated setting a metabolic activity level of 1.6 met, a clothing insulation equal to 1 clo during the winter period and 0.5 clo during the summer, an air velocity of 0.05 m s^{-1}, and the operative temperatures generated by TRNSYS output and relative humidity values calculated balancing internal vapour generation, outdoors relative humidity and mass exchanges. As it can be seen in Fig.s 6 and 7, the cases with lower operative temperatures (e.g., with uninsulated envelope and low internal gains in colder climates) are characterized also by lower PMV. In all cities, the cases with uninsulated concrete walls and low internal gains are also those with PMV closest to neutrality, and, therefore, those with lowest productivity losses. With the use of a cooling system, the values of maximum and third quartiles and, to a lower extent, of medians are lowered (Fig. 7), especially for Messina.

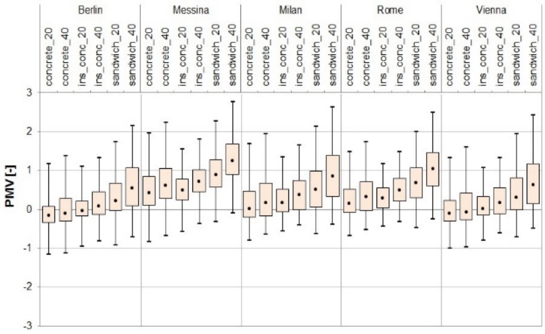

Fig. 6 – Distribution of hourly PMV for the cases without cooling system, during working hours

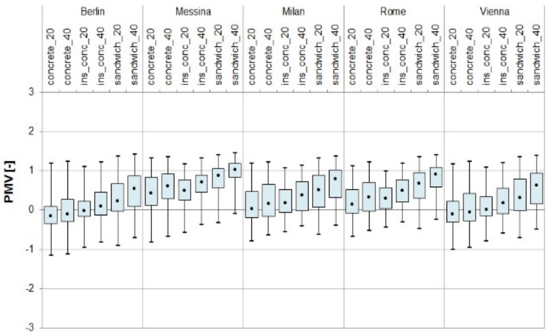

Fig. 7 – Distribution of hourly PMV for the cases with cooling system, during working hours

Fig.s 8 and 9 display the predicted percentage of dissatisfied, PPD, highlighting those cases with important fraction of time with PPD larger than 15 %, i.e., category C limit according to ISO 7730. In case of insulated envelope and high internal gain, the frequency of high PPD increases, especially for south Europe climates.

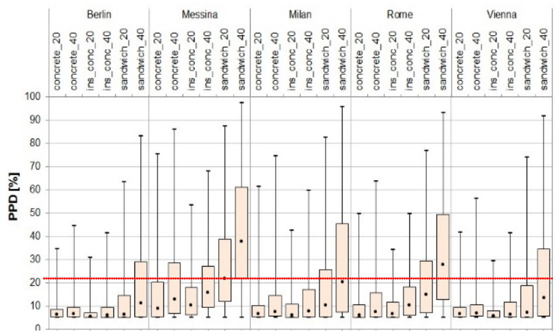

Fig. 8 – Distribution of hourly PPD for the cases without cooling system, during working hours. The red line indicates the limit of a category C environment (ISO 7730)

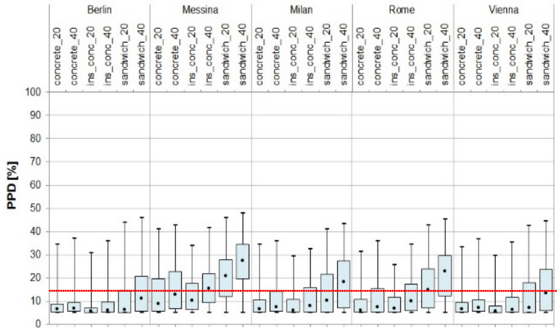

Fig. 9 – Distribution of hourly PPD for the cases with cooling system, during working hours. The red line indicates the limit of a category C environment (ISO 7730)

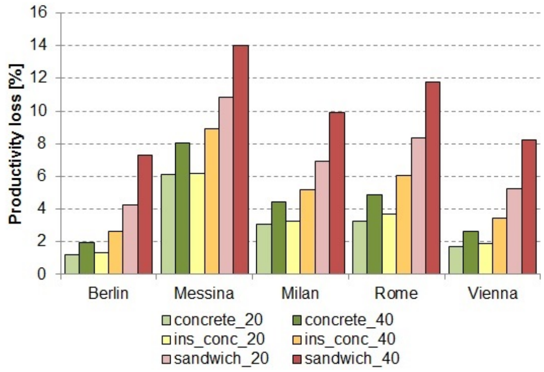

Fig. 10 – Annual average of productivity loss for the cases without cooling system

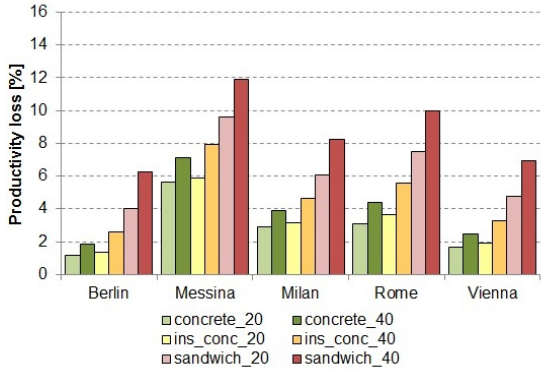

Fig. 11 – Annual average of productivity loss for the cases with cooling system

3.4 Annual and Seasonal Productivity Loss

The hourly productivity losses were calculated as a function of hourly PMV, according to Roelofsen model. As a result, the configurations characterized most frequently by lower PMV values, i.e., the cases with uninsulated envelope and low internal gains, have the lowest loss for while the opposite occurs with well-insulated components and high internal gains. As in Fig.s 10 and 11 and in Table 3, the cooling system can reduce the annual average of productivity loss, especially in Messina during the summer season.

Table 3 – Seasonal average increase of productivity after the installation of a cooling system

	Berlin		Messina		Milan		Rome		Vienna	
	winter	summer	winter	summer	winter	summer	winter	summer	winter	summer
Concrete_20	-	-	-	1.1 %	-	0.6 %	-	0.4 %	-	0.1 %
Concrete_40	-	0.2 %	-	2.1 %	-	1.5 %	-	1.3 %	-	0.6 %
Ins_conc_20	-	-	-	0.7 %	-	0.3 %	-	0.2 %	-	-
Ins_conc_40	-	0.2 %	-	2.1 %	-	1.5 %	-	1.3 %	-	0.6 %
Sandwich_20	-	0.8 %	-	2.6 %	-	2.3 %	-	2.3 %	-	1.5 %
Sandwich_40	0.2 %	3.2 %	0.5 %	4 %	0.2 %	4.1 %	0.4 %	4.2 %	0.2 %	3.8 %

3.5 Economic Analysis

Fig. 12 shows the Net Present Value for the investments related to the installation of a sensible cooling system in the productive buildings. As costs are expressed as positive values, a negative NPV means economic benefit, with the discounted savings overbalancing the initial costs. The investment is always profitable, except for 4 configurations, i.e., for the cases with either uninsulated and insulated concrete walls and low internal gains in Berlin and Vienna, for which the increase of productivity is null all over the year as seen in Table 3.

A sensitivity analysis was performed also on the number of workers, considering the economic convenience both in case of 20 and of 40 workers. As in Fig. 13, with fewer employees, the cases with concrete walls and low internal gains have null or positive NPV also in Milan and Rome. Moreover, in Berlin also those cases with high internal gains and concrete structures are no more convenient. As a whole, for the other cases all absolute values of NPV are reduced when compared to the base case with 30 workers. On the contrary, the opposite occurs with 40 workers (Fig. 14).

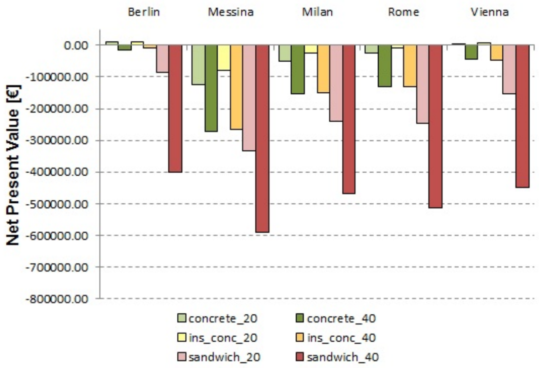

Fig. 12 – Net Present Values considering 30 workers

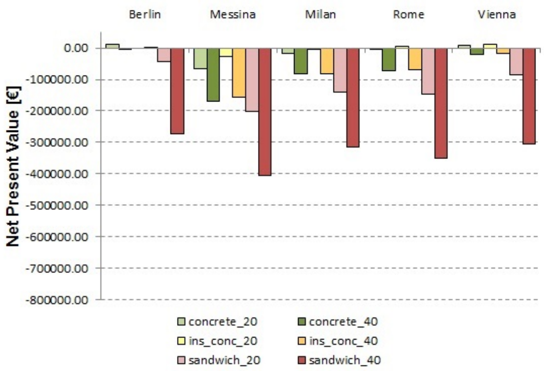

Fig. 13 – Net Present Values considering 20 workers

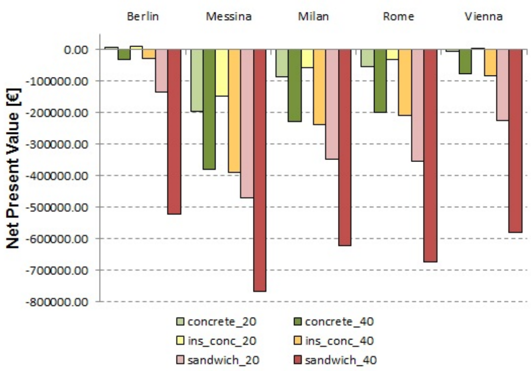

Fig. 14 – Net Present Values considering 40 workers

4. Discussions and Conclusions

This preliminary study focused on thermal comfort in productive buildings and potential improvement to productivity arising from the adoption of cooling systems, generally not present in such a kind of building. A parametric set of small-size productive buildings was simulated with TRNSYS, considering different European climates, kind of envelopes, as well as internal gains. The economic benefit of the cooling system was assessed by contrasting the higher achievable productivity rate with the additional investment and running energy costs. We observed that:

- there is a high risk of thermal discomfort by warm sensation because of internal gains, which depends on the specific machineries and type of process;
- this risk can be increased further in case of insulated envelope and, in particular, for the Mediterranean climates;
- a cooling system can successfully reduce the thermal discomfort, increasing the productivity rate up to 4 % in the most critical configurations during the summer season;
- the improvement of the thermal comfort conditions in the workplace are economically convenient in most scenarios, with the exception of the configurations with uninsulated envelope and low internal gains in Berlin and Vienna;
- even a small improvement in average productivity (e.g. 1-2 %) is sufficient to pay off the additional costs for space cooling.

In conclusion, investments in HVAC systems for the improvement of workers' thermal comfort conditions demonstrated to be an effective strategy to increase the productivity rate and gain competitive advantage. Further developments are expected to focus on actual case-studies, with the aim of assessing the limits of applicability of the Roelofsen correlation between productivity and thermal comfort to the different industrial activities as well as the influence of local comfort/discomfort on workers' productivity.

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