Interaction between Indoor Occupational Heat Stress and Environmental Temperature Elevations during Heat Waves

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ABSTRACT

Occupational heat strain is a public health threat, and for outdoor industries there is a direct influence from elevated environmental temperatures during heat waves. However, the impact in indoor settings is more complex as industrial heat production and building architecture become factors of importance. Therefore, this study evaluated effects of heat waves on manufacturing productivity. Production halls in a manufacturing company were instrumented with 33 dataloggers to track air temperature and humidity. In addition, outdoor thermal conditions collected from a weather station next to the factory and daily productivity evaluated as overall equipment efficiency (OEE) were obtained, with interaction between productivity and thermal conditions analyzed before, during, and after four documented heat waves (average daily air temperature above 24°C on at least three consecutive days). Outdoor (before: 21.3° ± 4.6°C, during: 25.5° ± 4.3°C, and after: 19.8° ± 3.8°C) and indoor air temperatures (before: 30.4° ± 1.3°C, during: 32.8° ± 1.4°C, and after: 30.1° ± 1.4°C) were significantly elevated during the heat waves ($p < 0.05$). OEE was not different during the heat waves when compared with control, pre-heat-wave, and post-heat-wave OEE. Reduced OEE was observed in 3-day periods following the second and fourth heat wave ($p < 0.05$). Indoor workers in settings with high industrial heat production are exposed to a significant thermal stress that may increase during heat waves, but the impact on productivity cannot be directly derived from outdoor factors. The significant decline in productivity immediately following two of the documented heat waves could relate to a cumulative effect of the thermal strain experienced during work combined with high heat stress in the recovery time between work shifts.

1. Introduction

A direct consequence of climate change is an increase in the frequency, duration, and intensity of extreme temperature events or heat waves. Heat waves cause heat strain, which may be uncompensable, resulting in deleterious effects on health and well-being. In occupational settings this will affect performance and, thus, work productivity (Kjellstrom et al. 2016; Lundgren et al. 2013). A recent systematic review and meta-analysis reported that during, or at the end of work under heat stress, 35% of workers experience occupational heat strain, while 30% of workers report productivity losses (Flouris et al. 2018a). However, occupational heat stress has been mainly studied to date in jobs associated with the military, construction, mining, agricultural, and metal industries (Brake and Bates 2002; Hunt et al. 2016; Jay and Brotherhood 2016; Krishnamurthy et al. 2017; Ryan and Euler 2017), as they include intense physical activity, wearing of protective clothing, and/or exposure to extreme ambient conditions. For outdoor workers it is well documented that high environmental heat strain has marked negative effects on workers' productivity (Ioannou et al. 2017; Sahu et al. 2013), whereas the effects on indoor workers are less clear and the impact more complex as industrial heat production and building architecture become factors of importance.

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To minimize the effect of thermal factors on productivity, conditions in the occupational setting must be regulated to maintain a state of workers' thermal comfort. This has been demonstrated by several studies that have included office workers (Akimoto et al. 2010; Lan et al. 2012; McCartney and Humphreys 2002). Needless to say, the settings and nature of work performed by office workers is quite different from that performed by workers in the manufacturing process and similar industries with large production halls and high heat generation from industrial processes. While the ambient conditions in the office may be adjusted and improved by including some simple behavioral adaptations, artificial air cooling, opening windows, ventilating the rooms, or adjusting clothing components, this is often not possible in large industrial environments and especially so at individual work stations close to the industrial machinery.

Cachon et al. (2012) assessed the productivity in 64 U.S. vehicle assembly plants during severe weather conditions over a 10-yr period. They concluded that high temperatures, among other severe weather conditions, reduce production and that in such conditions the existing cooling systems cannot maintain the indoor temperatures below 25°C. During weather conditions that result in temperatures in excess of 25°C, they concluded that recovery of productivity requires more than a week. Similarly, Sudarshan and Tewari (2014) observed decreases in manufacturing output at high temperatures (1%–3% drop per 1°C), which were significant and exhibited nonlinear relation to temperature. On that basis it may be surmised that manufacturing industries cannot maintain thermally comfortable ambient conditions ($\leq$25°C) during heat waves, resulting in reduced productivity, which may require more than a week to recover after such an extreme temperature weather event.

Climate change implies that heat stress issues will spread to larger geographical areas and increase in severity with more frequent occurrence and longer duration of heat waves (Morabito et al. 2017). In the ongoing European Heat-Shield project (Nybo et al. 2017) the effects of occupational heat stress in five key European industries, including agriculture, construction, manufacturing, tourism, and transportation, are evaluated in order to develop effective solutions to promote health, prevent disease, and maintain productivity of European workers. These industries represent 40% of European gross domestic product and employ over 50% of its population (OECD 2017). However, there are large differences in vulnerability to climate risks between these industries, and between companies within the same industry. Adaptive solutions for mitigating the effects of heat waves will vary significantly among companies (Kovacs 2011) and industries. Therefore, the present study focused on the manufacturing industry and evaluated the impact of indoor and outdoor absolute air temperatures during heat-wave periods on manufacturing productivity—as reflected in the overall equipment effectiveness (OEE) score—in an automobile parts manufacturing plant.

2. Methods

The study evaluated the effect of heat waves on OEE in the ''odelo Slovenija d.o.o.'' company (Prebold, Slovenia), manufacturing automobile rear lights. The company employs over 1500 people, the majority of which are involved in the production process. The production area encompasses 40 000 m^2, with five main interconnected halls. The building has a typical square shape with high ceilings (8–10 m) and flat roof with installed windows. The floor is concrete and the walls are made of insulated wall panels. The halls have ventilation systems that exchange the air between the indoors and outdoors and regulate humidity, which needs to be maintained within a curtain range to ensure the quality of the product. Exchange between the indoor and outdoor air is especially effective at greater temperature gradients, meaning that during the cooler seasons the indoor air can affectively be cooled by supplying outdoor cool air to warm indoor environment. To increase ventilation, roof windows are also used. Since the company operates 24 hours per day for 7 days per week (''24/7'') with similar steady production process throughout the day, the heat from the machinery is constantly generated and can only be partly removed by the existing ventilation systems. This becomes an issue during summer and especially during heat waves, when heat accumulation becomes too severe (~30°–32°C at the injection-molding stations throughout the day) to be handled by existing ventilation systems, with temperature gradient between the indoor and outdoor conditions too low to notably affect the temperature within the factory.

Work in the manufacturing process comprises plastic injection molding, metallization of components, and packaging/storage. Daily production process is conducted in three shifts, including morning (from 0600 to 1400 LT), afternoon (from 1400 to 2200 LT) and night (from 2200 to 0600 LT) shift. The workers involved in the molding and metallization process form four groups, with three groups involved in each of the three shifts, and one group resting. The workers change shifts every 4 days.

The present analysis focused on the manufacturing hall devoted to injection molding, as it has the greatest source of thermal energy and thus the highest measured indoor temperatures during normal weather conditions. Workers involved in the injection-molding process are required to perform moderate intensity work, wearing normal clothing (T-shirt and trousers). The workforce is predominantly female.

The analysis of OEE was conducted during the summer months (June, July, and August) in 2017. Measurements were also performed during a control period in May of the same year.

a. *Instrumentation and measurements*

To collect information regarding indoor and outdoor absolute air temperatures of the company, the manufacturing halls were instrumented with 33 MSR Electronics GmbH dataloggers, measuring air temperature and humidity. Each datalogger measured the air temperature close to the floor level (approximately 5 cm above the floor) and air temperature and humidity at head level (approximately 150 cm from the floor level), indicating potential thermal gradients at the individual workplaces. The factory is divided into three main halls, including plastic injection molding, metallization, and assembly line. Since the largest area of the factory is devoted to the injection-molding process, the majority of dataloggers (23 sensors) were installed in this hall, and the remaining 10 were in the metallization and assembly halls. Pilot measurements confirmed that the work stations in the injection-molding hall were the hottest; therefore the present study focused on the effects of heat waves on these workers. Apart from the dataloggers measuring air temperature and humidity in the factory, a Davis Instruments Corp. weather station was installed on the factory grounds. Temperature and humidity sensors sample and store data at 15-min intervals, whereas the weather station samples and stores data every 30 min. All data are automatically streamed to a data cloud, allowing further analysis.

Productivity reflected in the OEE score is a widely used standard for measuring manufacturing productivity. Despite its name, the score does not focus merely on equipment, but also encompasses the work conducted by the workers. The OEE score was used as an objective measurement of work efficiency, continuously calculated and monitored throughout the day for each of the working shifts. This method was considered as the least invasive and most acceptable by the companies' management and the workers, as it did not require extra effort and considered group performance, respectively. As explained by the companies' management, the OEE score is primarily driven by the human factor, since the machinery predominantly operates at an identical pace with planned stops throughout the day. As such, it was considered as reliable indicator of human performance, indicating potential alterations due to heat stress. Since performance can be influenced by various factors, nonrelated to temperature (such as motivation, experience, or acclimation), the OEE score was analyzed in different summer periods, including each heat wave with pre- and post-heat-wave scores to observe potential pattern in performance. It was presumed that any changes in performance, observed in similar time frames during hot conditions would indicate some level of heat stress, concomitant with or irrespective of other nonthermal factors.

OEE identifies the percentage of the manufacturing time that is truly productive, by including availability A, performance P, and quality Q. Availability takes into account planned and unplanned stops. An availability score of 100% means the process is always running during planned production time. Performance takes into account slow cycles and small stops. A performance score of 100% is achieved when the process time is running inline of maximal equipment cycle time. Quality takes into account defects (including parts that need rework). A quality score of 100% means that there are no defects (only good parts are being produced). In addition, OEE takes into account all losses. An OEE score of 100% means that the company is manufacturing only good parts, as fast as possible, with no stop time (Vorne Industries 2018). The exact formulas used to determine OEE in the present study were

$$\begin{aligned}\mathrm{OEE}\,(\%) &= \text{Overall Equipment Effectiveness}\\ &= A \times P \times Q\end{aligned}$$

such that

$$\text{Availability}\,A\,(\%) = \frac{\text{Actual production time (min)}}{\text{Planned production time (min)}} \times 100,$$

$$\text{Performance}\,P\,(\%) = \frac{\text{Actual number of produced parts}}{\text{Target number of produced parts}} \times 100, \quad \text{and}$$

$$\text{Quality}\,Q\,(\%) = \frac{\text{Number of good parts}}{\text{Number of produced parts}} \times 100.$$

A definition of heat wave needs to consider regional weather conditions and the climatology of a specific region. According to a recently issued heat-wave definition for Slovenia and based on the location of the odelo factory, located in Prebold (northeast Slovenia), a heat wave was defined as the average daily (24 h) air temperature equal to or exceeding 24°C on at least three consecutive days (Kljucevsek et al. 2018). This definition, considered for subcontinental climate, is used for central, northeast, and southeast parts of Slovenia. It was used to determine the occurrence of heat waves and for the analysis and interpretation of the indoor and outdoor temperature measurements.

b. *Analysis*

During the summer months of 2017, four documented heat waves were analyzed (Table 1; Fig. 1). A 1-week period in the beginning of May (spring) of the same year was used as a control period. This week best represented the outdoor air temperatures measured in the previous years.

For the statistical analysis indoor and outdoor air temperatures were averaged in 8-h bins, presenting the average temperature for each of the three shifts. Similarly, OEE was also analyzed for each shift within one working day. Indoor and outdoor air temperature and OEE data were analyzed during four documented heat waves, including also data from a 3-day pre-heat-wave period and a 3-day post-heat-wave period. A one-way analysis of variance (ANOVA) was used to compare the air temperature (indoor and outdoor) data between different shifts (morning, afternoon, and night shift) and between control (spring), pre-heat-wave, heat-wave, and post-heat-wave periods. Significant differences were analyzed by Tukey's honestly significant difference (HSD) test with $p < 0.05$ regarded as statistically significant. Given the nonnormally distributed OEE data, a nonparametric Kruskall–Wallis test was performed. When significant OEE differences between pre-heat-wave, heat-wave, and post-heat-wave periods were reported, a series of Mann-Whitney U tests were performed to locate these differences. The inflation in the type-I error rate was controlled by using Bonferroni adjustment, dividing the p value of 0.05 with the number of comparisons (pre-heat-wave, heat-wave, and post-heat-wave periods). When running the Mann–Whitney U test, $p < 0.017$ was considered as statistically significant. Data were analyzed using the IBM SPSS 23.0 software.

3. Results

a. *Outdoor air temperature (°C)*

Outdoor air temperature was lower during the control period in spring (14.3° ± 2.8°C) than during the summer months (22.8° ± 4.9°C; $p < 0.001$). It did not significantly differ among the four heat waves. During the first heat wave, outdoor air temperature was higher relative to pre-heat-wave air temperature ($p = 0.006$) but not relative to post-heat-wave air temperature ($p = 0.076$). During the second, third, and fourth heat waves this was reversed, with outdoor air temperature being higher relative to post-heat-wave air temperature ($p = 0.048$, $p < 0.001$, and $p = 0.009$, respectively) but not relative to pre-heat-wave air temperature ($p > 0.05$). Throughout the summer, the outdoor air temperature differed between all three shifts, with the lowest temperature measured during the night and the highest in the afternoon (morning shift: 23.4° ± 3.7°C, afternoon shift: 26.0° ± 4.5°C, and night shift: 17.6° ± 3.5°C, $p < 0.001$).

TABLE 1. Periods of documented heat waves, their duration, and average daily outdoor air temperature (including all heat-wave days).

	Period	Duration (days)	Mean temperature (°C)
Heat wave 1	20–24 Jun	5	25.2 ± 4.2
Heat wave 2	6–11 Jul	6	24.8 ± 4.5
Heat wave 3	20–23 Jul	4	25.1 ± 4.1
Heat wave 4	31 July–5 Aug	6	26.6 ± 4.7

b. *Indoor air temperature (°C) and relative humidity*

Throughout the spring and summer months, the indoor air temperature and vapor pressure were continuously higher (31.3° ± 1.9°C, 4.4 kPa, and $p < 0.001$) and relative humidity (RH) was continuously lower (35% ± 6%; $p < 0.001$) relative to the outdoor conditions, respectively (22.3° ± 5.2°C, 2.6 kPa, and 68% ± 19%). The indoor air temperature was lower during the spring (29.0° ± 0.8°C; $p < 0.001$) relative to summer months (31.5° ± 1.9°C). It was higher during all heat waves ($p < 0.001$) relative to the air temperature measured before and after the heat waves (Table 2). Indoor pre-heat-wave air temperature was similar to the temperature measured after the heat wave (Table 2; $p > 0.05$). During all heat waves, similar indoor air temperature was measured (Table 2). Indoor air temperature was lower during the night shift (29.9° ± 1.5°C; $p < 0.001$) relative to temperatures measured in the morning (31.8° ± 1.6°C) and afternoon (32.2° ± 1.9°C) shifts.

c. *Overall equipment effectiveness (%)*

Irrespective of the outdoor and indoor air temperature differences between the spring and summer months, the OEE was not affected by seasons, with similar OEE measured during spring and summer (Table 2). The only exception was the OEE measured after the fourth heat wave (69% ± 9%), which was significantly lower than the one measured in spring (82% ± 6%; $p = 0.009$). During the heat waves, OEE was similar to the OEE measured during the spring control period. A drop in OEE was observed after the second heat wave was already completed, namely in the post-heat-wave period. This drop was from 84% ± 7%, measured during the heat wave, to 78% ± 4% ($p = 0.014$) in the period after

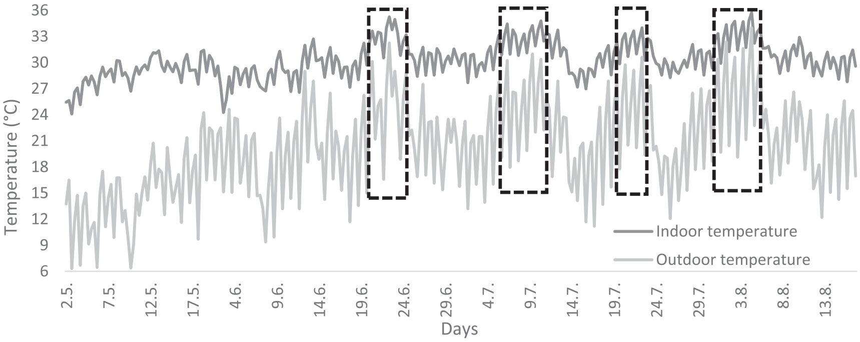

FIG. 1. Average indoor and outdoor air temperatures per shift (8 h) during spring and summer 2017, with four documented heat waves (indicated by the dashed boxes).

the heat wave. A substantial drop in OEE was also observed after the fourth heat wave, decreasing from 79% ± 8% to 69% ± 9% ($p = 0.021$), which, however, did not reach our Bonferroni-adjusted statistical significance level of 0.017. During the four heat waves, similar OEE was measured (Table 2; $p > 0.05$). Irrespective of the indoor and outdoor air temperature differences among the three shifts (morning, afternoon, and night), no difference in OEE between the shifts was reported throughout the summer (morning shift: 78% ± 8%, afternoon shift: 80% ± 9%, and night shift: 79% ± 9%, $p > 0.05$).

4. Discussion

The main finding of this study is that industrial productivity was affected in periods following heat waves rather than being directly affected during the four heat-wave periods representing 21 working days in total. No direct correlations between the varying outdoor and indoor temperatures and OEE for morning, afternoon, and night shifts were observed. However, in the periods following two of the four documented heat waves there was a significant drop in OEE, suggesting that insufficient recovery and interaction between occupational exposure and overall daily heat strain (outside working hours) are of importance for the integrated impact on indoor workers.

The study observed less fluctuation in the summer indoor factory air temperature (31.5° ± 1.9°C) than in the outdoor air temperature (22.8° ± 4.9°C). This was also evident when comparing air temperatures between spring and summer, with average indoor air temperature differing by 2.5°C and outdoor air temperature by 8.5°C between spring and summer. Given the 24/7 operating time of the factory, the injection-molding halls cannot cool down, even when the outdoor temperatures drop. The analysis indicated the difference in the outdoor air temperature between all three shifts, with the lowest

TABLE 2. Indoor and outdoor average air temperature (°C) and overall equipment effectiveness (%). (During = heat wave; Pre = the 3 days before heat wave; Post = the 3 days after heat wave.)

		Indoor temperature (°C) ± std dev	Outdoor temperature (°C) ± std dev	OEE (%) ± std dev
Spring	Control	29.0 ± 0.8[a]	14.3 ± 2.8[a]	82 ± 6
Summer heat wave 1	Pre	29.7 ± 1.5[b]	19.2 ± 4.9[b]	70 ± 12
	During	33.0 ± 1.4	25.2 ± 4.2	85 ± 9
	Post	30.1 ± 1.3[b]	21.0 ± 3.8	79 ± 9
Summer heat wave 2	Pre	30.7 ± 1.4[b]	21.4 ± 4.5	78 ± 6
	During	32.8 ± 1.3	24.8 ± 4.5	84 ± 7
	Post	30.3 ± 2.2[b]	20.2 ± 4.6[b]	78 ± 4[d]
Summer heat wave 3	Pre	30.7 ± 1.2[b]	21.9 ± 5.2	76 ± 3
	During	32.3 ± 1.3	25.1 ± 4.1	81 ± 7
	Post	29.4 ± 0.8[b]	17.4 ± 3.0[b]	80 ± 8
Summer heat wave 4	Pre	30.6 ± 1.2[b]	22.7 ± 3.9	76 ± 9
	During	33.1 ± 1.6	26.6 ± 4.7	79 ± 8
	Post	30.6 ± 1.1[b]	20.8 ± 3.2[b]	69 ± 9[c]

[a] Significant difference between control (spring) and summer period.
[b] Significant difference relative to heat-wave air temperature.
[c] Significant difference relative to control (spring) period.
[d] Significant difference relative to heat-wave OEE.

temperature measured during night and highest in the afternoon. The indoor temperatures were significantly lower during night when compared with the temperatures measured in the morning and afternoon.

Interestingly, there appears to be no direct effect of the heat waves on OEE. A drop in OEE was observed only after the end of the second and the fourth heat waves. The duration of these two heat waves was 1–2 days longer (Table 1) when compared with the first and third heat wave, respectively, suggesting that this slightly longer heat exposure may have potentially affected the OEE score in the days after the heat waves. It was hypothesized that the night shift could potentially be more productive during heat waves because of a drop in the indoor and outdoor temperatures, but the analysis indicated no difference between the shifts.

As explained earlier, OEE is a diagnostic tool, depending on three components, including availability and performance of the machinery and quality of the product (Vorne Industries 2018). A positive correlation between human error in relation to all three components as well as the overall OEE has previously been reported (Ngadiman et al. 2016). According to the management at the odelo factory, with rare exceptions, machine availability and performance in their company are constant, and as a consequence the manufacturing process runs at the same pace all the time. It is predominantly the quality component that affects their OEE score. The workers at the injection-molding work stations are in charge of examining and evaluating the quality of the product and removing the bad parts before moving to the next process. The overall manufacturing process in the company is therefore substantially human dependent.

As observed, OEE was not affected during any of the documented heat waves. It was affected after the end of the heat waves. Because of their constant exposure to warm ambient temperature (31.5° ± 1.9°C) at work with minor temperature fluctuations, workers seem to be well adapted to the ambient temperatures, as reflected in the stable OEE values with no differences between different shifts.

To appreciate this post-heat-wave decrement in OEE scores, the workers' exposure to the environmental conditions during all the hours of the heat wave must be considered rather than focusing only on the 8 h of each day that they are at work. Namely, during normal weather conditions, the outdoor air temperatures are significantly lower than those at the work stations. As a result, the workers can recover from any level of heat strain developed during the 8-h shift, due to the 16-h exposure to normal ambient conditions at home and at activities outside of work. Appropriate recovery from the heat strain of the 8-h work shift will ensure that the workers can perform optimally the following day. This is reflected in an unchanged OEE score during normal weather conditions. During periods of heat waves, the workers may not be able to recover completely from the heat strain resulting from the 8-h work shift during the 16-h period away from work. Namely, the outdoor temperatures can be higher than those in the factory. Also, the conditions in their dwelling may not offer recovery from the heat strain. As a consequence, a longer period of heat exposure may affect OEE because of a cumulative effect that results from an inability of the workers to recover properly after leaving work. This cumulative effect of heat waves may result in fatigue and thus a drop of OEE after a certain period. The cumulative effect of heat waves is usually associated with mortality as the most extreme indicator (Rocklov et al. 2012; Urban et al. 2017), whereas its effect on fatigue and consequent reduced productivity in industrial settings does not seem to be generally well recognized.

High ambient temperatures at home with no possibility of temperature regulation with air conditioning can contribute to a poor sleep quality (Obradovich et al. 2017; Okamoto-Mizuno and Mizuno 2012), resulting in reduced physical and mental performance (Ahrberg et al. 2012; Andrade et al. 2016; Cedeño Laurent et al. 2018). An important issue that needs to be considered is the socioeconomic status of people. Workers with social disadvantages can be affected greatly by temperature extremes, particularly if there are financial impediments in maintaining thermal comfort (Hansen et al. 2013). The odelo management also addressed religious and diet aspects that could potentially affect work.

From the results of questionnaires administered to the workers at the odelo factory, we recently reported (Pogačar et al. 2018) that a greater portion of females than males exhibit heat-related symptoms. This type of result needs to be qualified, as it may project wrong information to companies regarding employment policy (namely, that females might have a predisposition to heat-related problems) (Flouris et al. 2018b). There is evidence that in Slovenia, as a result of traditional gender roles, women carry a greater share of the burden of domestic chores than do men (Jogan 2011; Kanjuo-Mrčela and Černigoj-Sadar 2007). During periods of heat waves, this added physical burden may impair their ability to recover from the heat strain accumulated during their 8-h shift at the factory when compared with men. The cumulative effect of heat waves, socioeconomic status, diet, and hypohydration (Piil et al. 2018), as well as traditional gender roles, are all aspects that can potentially affect people's performance.

It is clear that HVAC systems are tremendous consumers of energy in big industrial halls and are not able to maintain the indoor temperature below a certain level during extreme weather conditions (Cachon et al. 2012). In such cases, personal cooling strategies, allowing individual adjustments, have to be considered. The company in the present case (odelo) has already implemented a number of actions, including free bottled water, water-drinking recommendations, air-conditioned rooms where workers can cool during breaks, longer breaks, free swimming-pool tickets, and free ice cream at lunch. As such, it can serve as a platform for other companies that are dealing with similar heat-related problems. Other strategies, not feasible in the present case, could also include shifting production process to cooler parts of the day and implementing extensive ventilation at night.

It should be appreciated that there is great individual variation in the magnitude and severity of heat strain associated with heat stress. This fact underscores the importance of raising awareness among the workforce and stakeholders about the effect of heat waves accompanying climate change, as this will ultimately benefit the workers and management, maintaining health, well-being, and productivity. Health education could improve risk awareness (Ma et al. 2016; Matthies and Menne 2009), with actions taken at different levels, including meteorological early warning systems, medical and public interventions, and upgraded urban and infrastructure planning (Matthies and Menne 2009). Moreover, health education considering climate change should become a part of the educational system, with young generations already competent when entering the labor market.

5. Conclusions

The present analysis of the interaction between environmental (outdoor) and indoor air temperatures and their impact on productivity at the odelo factory signifies the complexity of the problem but also provides insight and a framework for addressing occupational heat strain for indoor workers. There is still a paucity of data regarding the effects of climate change in manufacturing industries, with the usual emphasis being on outdoor occupations and occupations dealing with extreme ambient temperatures. This area therefore crucially needs further exploration.

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