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Heat Economics: How to Reduce Worker Productivity Losses?

Yufei Wang[1], Gaurav Toor[2]

[1]Valley Christian High School, San Jose, California, USA
[2]Department of Government, Cornell University, Ithaca, New York, USA
Email: sammiwang026@gmail.com

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Abstract

Under climate change, heat-induced stress became a common phenomenon where the condition increases workers' exposure to heat-related illness and leads to a decrease in work productivity. As a result, heat-related work productivity loss greatly impacts economies today, both developing and developed countries alike. However, many of the popular mitigation strategies used in current societies today are inaccessible due to high costs, impose danger to individual health, and are not sustainable for the planet. This research explores the weaknesses of current widely-used mitigation methods and evaluates feasible alternative approaches that are more effective long-term for heat mitigation and sustainability. By analyzing an array of case studies, this research concludes that countries should adopt a set of multiple sustainable methods, improving both short-term heat stress and long-term sustainability to benefit their economies.

Keywords

Heat Stress, Work Productivity, Economy, Sustainability, Heat Mitigation

1. Introduction

Heat stress occurs when the human body cannot further tolerate external heat, such as workplace temperature. Influenced by both psychological and physical factors, individuals who experience heat stress will see themselves facing a decrease in productivity. With an estimated global economic loss projected to range from 0.31% to 2.6% of the global GDP in 2100, heat-related work productivity loss (WPL) is a rising global concern and impacts a country's labor health, labor supply, and overall macroeconomy (Zhao et al., 2021). Most existing research on this topic explores the direct impact of heat stress on individuals, as well as the economic loss associated with heat-related WPL (Zhao et al., 2021). However, there is a lack of research as to the methods that could be implemented to mitigate heat-related WPL while minimizing adverse environmental impact and improving the overall economy.

How do we decrease heat-related work productivity losses (WPL)? While evaluating this question, it is important to consider the numerous underlying factors contributing to heat-related productivity loss. This question seeks to understand the relationship between workplace heat exposure and economic impact, and its influence on individual workers. Additionally, due to increasing climate change and temperature, this question becomes more time-sensitive to answer, especially for developing countries seeking the most cost-effective method to combat this issue.

Although providing thermoregulatory devices, enforcing work-time shifting, and introducing heat stress awareness programs are possibilities, this paper argues that sustainable solutions (such as vertical gardens, shades, and ventilation) are the most effective approaches as they are environmentally sustainable, improve psychological conditions, and are cost-effective.

To evaluate these methods and their effectiveness, we will closely examine the reasons for heat-related productivity loss. Under extensive heat conditions, workers may need to take longer breaks in between shifts to prevent heat strain. Additionally, individuals may also experience vigilance that leads to injuries or suffer psychologically from dissatisfaction with the work environment due to high heat. All of the above factors will lead to decreased work efficiency, lost work time, and lower work satisfaction, resulting in an overall decrease in productivity, output, and production, thus weakening the economy. Additional spendings related to this issue also include compensation costs in relation to injuries from heat, occupational expenses (due to shifting working hours), and labor loss due to worker resignations.

This paper seeks to determine the most effective approach by first looking at alternative explanations and addressing the positives and negatives of current methods. Then, based on case studies, we will evaluate sustainable mitigation methods and propose a viable measure by examining economic data after those methods were implemented. Finally, the paper will conclude with a summary of the evidence and propose future research directions on this topic.

2. Alternate Explanations

2.1. Alternate Explanation I: Air Conditioning

Air conditioning (A/C) is a popular heat mitigation method that offers quick and effective cooling in an indoor environment. A/C helps maintain and regulate temperature in both commercial and residential settings. In industrial workplaces, air conditioning can assist with protecting heat-sensitive equipment and machinery from overheating.

Though air conditioning can effectively cool down the environment in a short period of time, this method is only effective in indoor spaces. Due to this, the A/C is impractical for outside workers, who experience more direct exposure to heat. The method presents several limitations to its applicability. In low and middle-income countries, access to air conditioning will be difficult due to the lack of financial resources (Borg et al., 2021). High costs associated with purchasing, installing, and operating the A/C make this approach inaccessible for many regions in developing countries. Along with the lack of purchasing power, these countries also have a limitation in access to electricity, making the A/C solution even more impractical. The sample that took place between 1990 and 2010 shows that only about 5 percent of households in India have air conditioning (LoPalo, 2020).

Additionally, air conditioning also has its limitations in maintaining long-term physical health. As studies show, long-term exposure to cooling systems like A/C decreases individuals' resistance to heat (Zhao et al., 2021). The vulnerability to high temperatures, caused by the decrease in heat tolerance, could be harmful during periods of extreme heat or times without mitigation methods in the workplace. Additionally, as Zander and Mathew (2019) demonstrated, the estimated economic loss was twice as high for those who had air conditioning at home than for those who did not (Zhao et al., 2021). This economic loss indicates that the air conditioning method cannot be heavily dependent upon as an endurable method.

2.2. Alternate Explanation II: Work Time Shift

Shifting work hours has been a sufficient heat-mitigation strategy in low and middle-income regions, which describes adjusting the typical work schedule to avoid peak daytime heat (Takakura et al., 2018). This approach would ensure a cooler temperature around the middle of the day. An earlier start time and cooler temperature may lead to a decrease in operational costs in usage for thermoregulatory devices or the overall use of electricity. Additionally, with less exposure to direct sunlight and heat, workers are less prone to injuries such as heat-induced fatigue. Workers may also experience an increase in work satisfaction in a suitable work environment.

However, this approach would only be effective if working hours were shifted well before dawn (Takakura et al., 2018). Due to global temperature rising, early morning is often the only time during the day with sufficiently cool temperatures that can significantly decrease heat stress. At the same time, implementing such early hours may lead to an increase in other electrical costs, such as lighting solutions for the dark. Shifting hours early can also lead to economic and operational deficiencies, with costs spent on managing shift schedules and the potential increase in maintenance costs, required for devices to operate in abnormal hours.

Shifting working hours can only be considered as an improvement strategy, and not as a decisive mitigation tool. Though research has shown that productivity loss decreased during shifted working hours compared to the standard hours (8 a.m. to 5 p.m.), PL is not completely mitigated (Morabito et al., 2021). While PL still occurs amongst workers, there is an increased chance of worker dissatisfaction with working in the early mornings. This method may be sufficient in developing areas, but shifting working hours will have little effect in terms of drastically reducing productivity loss on either a large scale or in developed countries. A versatile method is still needed to effectively reduce and mitigate heat stress.

2.3. Alternate Explanation III: Heat Stress Awareness Programs and Miscellaneous Methods

Heat stress awareness programs, often used by corporate companies, are initiatives designed to educate workers on heat-stress management and promote awareness of practices to prevent heat-related injuries (Borg et al., 2021). These programs often include exercises to recognize signs of heat-induced illness and encourage the use of preventive methods such as hydration and taking breaks under shades. By enforcing such programs, companies can foster a healthy environment that prioritizes worker safety and well-being.

However, heat stress awareness programs rely on specific company cultures to ensure their success. Results can vary depending on different workforce dynamics, and the program's effectiveness relies solely on employee compliance and ongoing reinforcement by the company. Such programs require constant communication, training sessions, workshops, and management. Because of this, heat stress awareness programs are only suitable for large corporate companies with high operating budgets for the required reinforcements (Borg et al., 2021). Smaller companies or those in developing countries may struggle with the lack of resources to execute successful and effective programs.

However, heat stress awareness programs have their benefits. The direct results of implementing such programs can lead to a decrease in the number of Occupational Health Indicators (OHIs) for outdoor workers and compensation costs in cases of injuries (Borg et al., 2021). However, these programs themselves require a costly investment to cover high expenses in training and program fees. To add on, programs must be recurring and implemented often as companies will constantly recruit new employees. The high level of investment is not justified when considering its measured impact.

Based on the analysis of alternative arguments, this paper concludes that current mitigation methods are limited in many ways. In comparison, a range of sustainable solutions, such as fanning, green roofs, and shades, will be the most effective in combating heat-related productivity loss as it is cost-effective, sustainable for long-term heat emissions, and accessible.

3. Methodology

The field addressed by this paper suffers from a notable deficiency in relevant research, resulting in a dearth of usable data. Specifically, there is a significant gap in studies examining the adaptive effects of continuous heat exposure on the human capacity to perform manual and cognitive work, which does not allow confirmatory research to be a viable option (Ioannou et al., 2021). Because of this, research methods such as using quantitative data, sampling, or a single case study are not feasible.

A case study is a comprehensive examination of a single unit, offering detailed contextual analysis and insights into a specific phenomenon within real-world contexts (Gerring, 2004). The exploratory method, a type of research approach to navigating case studies, focuses on exploring new topics and proposing hypotheses on subjects that have not been rigorously tested (Gerring, 2004). In contrast to confirmatory research, exploratory research generates new understandings instead of verifying or refuting existing theories. This paper will employ qualitatively driven diverse case selection to study various effects of the proposed sustainable solutions in their ability to combat heat mitigation and lower productivity loss.

In order to capture a comprehensive view of the effectiveness of sustainable solutions for heat mitigation and work productivity, this paper will examine case studies from a diverse range of industries and geographical regions, both high and low-income countries, such as India and the United States. Developing countries are inclined to emulate the same manufacturing trajectory as developed countries; as their policies converge, employing an array of case studies will achieve the same effect for different countries.

Additionally, selected case studies will include an analysis of industry sectors, such as manufacturing, with each facing a growing problem of carbon emission and lack of work productivity as a result of heat. This paper strives to employ a global perspective on the phenomenon, showing the effectiveness of sustainable solutions in various contexts.

4. Evidence

Labor productivity loss from heat mitigation is a complex issue to solve. As countries each have various conditions, a general method cannot be applied to both developed and developing countries alike. In addition, current popular methods may provide immediate and small-scale improvements but do not account for long-term sustainability impacts. Through studying a qualitatively driven diverse case selection, we may generalize that in terms of (1) cost-effectiveness, (2) long-term sustainability, and (3) psychological improvements, sustainable methods are holistic options to mitigate heat-induced productivity loss by all countries.

4.1. Cost-Effectiveness

Current popular methods, such as air conditioning, work time shifts, and heat awareness programs all vary in total cost-effectiveness. Methods such as air conditioning and traditional cooling systems require significant initial investments in installation, maintenance, and energy consumption fees. Solutions that depend on human resources, such as heat awareness programs, require a large amount of human capital that incurs additional costs. In contrast, popular methods of sustainable solutions are more cost-effective in the long-term scope and for future operational costs. Sustainable alternatives to the traditional methods leverage passive cooling techniques that require less energy consumption.

It is important to note that sustainable methods are costly in the short term (Heerwagen, 2000). Natural ventilation, a method that leverages the natural air flow of carefully designed infrastructure, requires a high amount of cost for designing the infrastructure to obtain the perfect dimension, orientation, and height. However, once the solution is implemented, natural ventilation will process on its own with zero costs associated. Though sustainable methods may seem to have a high cost at the initial implementation stage, they significantly reduce future operational costs in the long term, making them appealing and available for countries at lower income levels.

Another sustainable option is electric fans. Fanning, after installation, requires less electricity and maintenance, thus requiring fewer recurring fees. As the demand for energy consumption decreases, operational costs become minimal. Additionally, in an experiment in a Southeast Asia occupational environment, electric fans yielded an 11% improvement in work output (Jay et al., 2019). The cost-effectiveness of electric fans over the A/C alternative can be shown through a case study, modeled after factory conditions in India based on the previously mentioned experiment.

For this case study, it is assumed that the factory is a medium-sized space of 8000 square feet. For industrial fans with 377,000 CFM (Cubic Feet Per Minute), it can effectively cover the space with one unit. For one industrial A/C, with the given condition that 12,000 BTU (Cooling Capacity) units will cool a 400- to 600-square-foot, 3 units of A/C with 66,000 BTU are required (**Table 1**).

Table 1. Comparison of Short-term and Long-term costs associated with Fanning and the A/C system in a Medium-Sized Factory in India.

Method	Cost (₹)	Cost After One Year of Operation (₹)	Cost After Five Years of Operation (₹)
Fanning	₹150,000 (initial cost for 3 units) + ₹46,000/year (operation cost)	₹196,000	₹380,000
Advanced systems (A/C)	₹90,000 (initial cost for 3 units) + ₹200,000/year (operational cost)	₹290,000	₹1,090,000

Costs are calculated under conditions:

- 12 hours per day in operation.
- ₹7 per kWh.

This case study shows that for factory or in-door workspaces, employing fanning as the main heat mitigation strategy is cost-effective, both in the short and long term.

Green buildings, sometimes known as sustainable buildings, employ environmentally responsible designs that effectively maximize energy use. With characteristics such as adequate ventilation and appropriate temperature control, green buildings show significant economic benefits through employee retention and greater productivity under ideal conditions. Increased productivity and reduced sick time associated with green buildings can yield net present value (NPV) benefits ranging from $37 to $55 per square foot; for owner-occupied buildings, these benefits can be even more significant (Miller et al., 2009).

This solution can yield both cost-reduction and value-added benefits. For the long-term operation, the Herman Miller building performance data demonstrated a 7% decrease in natural gas costs and an 18% decrease in electricity costs on a square foot basis for green buildings (Heerwagen, 2000). Due to the design of green buildings, such as increasing natural airflow, there is a reduced cost for companies on building-related illnesses like Sick Building Syndrome.12 These energy-efficient buildings solve common problems in workspaces. In one research, a provider of professional liability insurance paid more than $24 million for claims related to heating, ventilation, and air conditioning between 1989 and 1993 (Heerwagen, 2000). Such problems are often associated with underheated buildings with inadequate ventilation or cooling, which are very problems that green buildings address.

4.2. Sustainability

The methods countries use for heat mitigation must be sustainable to avoid worsening climate change, which is a major cause of the heat stress phenomenon and productivity losses. Climate change, a rising problem in the 21st century, imposes an existential threat to human health. Health impacts from extreme weather, especially high global temperatures, have increased the scale of heat-related mortality and morbidity, imposing great threats to economies by affecting human capital (Zhao et al., 2021). The current climate is a main contributing factor to the rising heat and overall decline in work productivity.

While traditional methods can be effective in the short term, these methods often contribute to worsening climate change through their emissions and energy use. As stated by the International Energy Agency, industries with the highest carbon emissions include energy production, transportation, manufacturing, and agriculture. In research done on the Chinese economy, China's CO_2 emissions from fuel combustion were 7999.6 million tons alone in 2011 and accounts for 25.4% of global emissions, specifically emitted from the iron and steel industry (Lin & Wang, 2015). Along with carbon emission, the energy consumption of the same industry is also substantial, with 588.97 million tons of coal equivalents making up 29.39% of total consumption in the manufacturing industries (Lin & Wang, 2015). With rapid economic development, the increase of CO_2 emissions will inevitably also increase in the near future.

Carbon emission affects a country's economy directly. According to climate model outputs that focus on carbon emission, individual countries experience a wide range of annual labor productivity losses due to an increase in heat exposure, ranging between less than 0.1 to more than 6% of total GDP per trillion tonnes of carbon (TtC). High-income countries, such as Canada, Germany, and New Zealand are affected with less than 0.1% of productivity loss per unit emission; countries such as India and Thailand experience losses of 3% - 5% of total GDP per year per TtC (Chavaillaz et al., 2019). Countries located in regions exposed to the impacts of climate change, as well as lower-income countries, are the most vulnerable to these economic effects.

The A/C method is a traditional method that consumes electricity and emits carbon output. The estimated carbon emission of A/C, and its economic loss for China—an Asian developing country—can be calculated through a case study.

Existing data:

- Approximately 60% of Chinese households use A/C
- Per estimate, average A/C unit consumes ~ 1.2 kWh per hour
- China's grid emits approximately 0.582 kg of CO_2 per kWh
- Similar to India and Thailand, China's growing economy experiences a ~3% loss due to productivity loss per unit emission
- China's fluctuating temperature, mostly due to industrial activity, climbs up to 18˚C - 28˚C (65˚F - 82˚F) during summer days. For this case study, it is assumed that the A/C is ran for 6 hours a day during summer time of extreme heat, for ~120 days.

Total emission:

$$1.2\ \text{kWh/hour} \times 6\ \text{hours/day} \times 120\ \text{days/year} \times 0.582\ \text{kg}\ CO_2/\text{kWh}\ 502.8\ \text{kg of}\ CO_2\ \text{per house}$$

With an estimated 474 million households in China, 60% approximate totals to ~280 million households with A/C use.

$$502.8\ \text{kg of}\ CO_2\ \text{per house}\ 280\ \text{million households} = 140.8\ \text{million tonnes of}\ CO_2$$

In terms of the impact of productivity loss, it can be calculated using China's GDP of 17.96 trillion USD.

$$0.03 \times 17.96\ \text{trillion USD} = 539\ \text{billion USD/year}$$

As shown through this case study, carbon emissions from the A/C method in developing countries, such as China, can substantially impact economies negatively.

Effective methods for heat mitigation could be implemented in the previously mentioned industries to increase work productivity, thus improving the economy. By decreasing potential working hours and increasing productivity output via heat-mitigating methods, these industries can increase efficiency and limit carbon emission volumes.

Natural ventilation, for example, utilizes design features to enhance airflow and reduce the need for mechanical cooling. This method requires adequate infrastructure design and urban landscape to combat the urban heat island effect. Natural ventilation considers design features like dimensions and orientation of windows to maximize air inlet; likewise, the orientation of the building will increase cross ventilation of the environment. This passive and all-natural ventilation method significantly decreases the dependency on electricity-powered cooling systems, limiting greenhouse emissions and energy resource use.

Traditional methods lack sustainability. Air conditioning systems, requiring high energy and electricity consumption, contribute significantly to greenhouse gas emissions and environmental degradation. As the A/C method increases human dependency, this method will only incur more costs and impose a worsened impact on climate change. However, it is important to note that some traditional methods, such as work time shifts, are sustainable options. Regardless, these methods are generally not effective—a work time shift can only be effective when the hour is shifted early dawn while requiring additional costs in lighting the dark workplace during irregular hours. Although sustainable, they fail to fulfill other categories to reduce heat stress, such as overall effectiveness.

4.3. Physiological Improvements

A rising global temperature ultimately results in growing heat stress amongst developing and developed countries, thus lowering work productivity in its effect on workers' physical and mental health (Zhao et al., 2021). A promising solution must be effective in reducing individual heat impact, easily adaptive, and positively influencing workers in their psychological aspects to maintain the health of the workforce.

As mentioned, the A/C system decreases individual heat tolerance over time and increases dependency. Though A/C can rapidly cool down body temperature, the fanning method is a better alternative for the psychological health of workers. A fan can be tailored to the environment by directing airflow toward specific workers rather than cooling an entire area. Fans can also be conveniently transported to remote work sites for specific cooling areas (Morris et al., 2020).

Green buildings are highly effective in increasing worker productivity and satisfaction. Design strategies such as increased access to daylight and window views can lead to positive well-being, stress reduction, and the potential impact on cognitive functioning (Heerwagen, 2000). These characteristics such as increased daylight exposure, views, and contact with nature are key proponents of human resource sustainability and can be considered long-term employee benefits. In terms of human health, green buildings mitigate factors associated with Sick Building Syndrome, which lowers productivity due to acute discomfort and illness (Heerwagen, 2000). This solution significantly enhances workers' psychological well-being, which directly translates to increased productivity.

Green buildings are used primarily in developed countries due to their costly initial investment. A case study conducted in Holland, Michigan, can demonstrate Green buildings' effectiveness in increasing work productivity by raising work satisfaction (Heerwagen, 1998). After moving from the old building into a new green facility, a survey was conducted for workers to rate their satisfaction in a variety of dimensions. 262 workers completed the survey, spanning those from manufacturing and those from the office areas (**Table 2**). Within the survey, workers are also asked to report their physical well-being in relation to the difference in work environment (**Figure 1**).

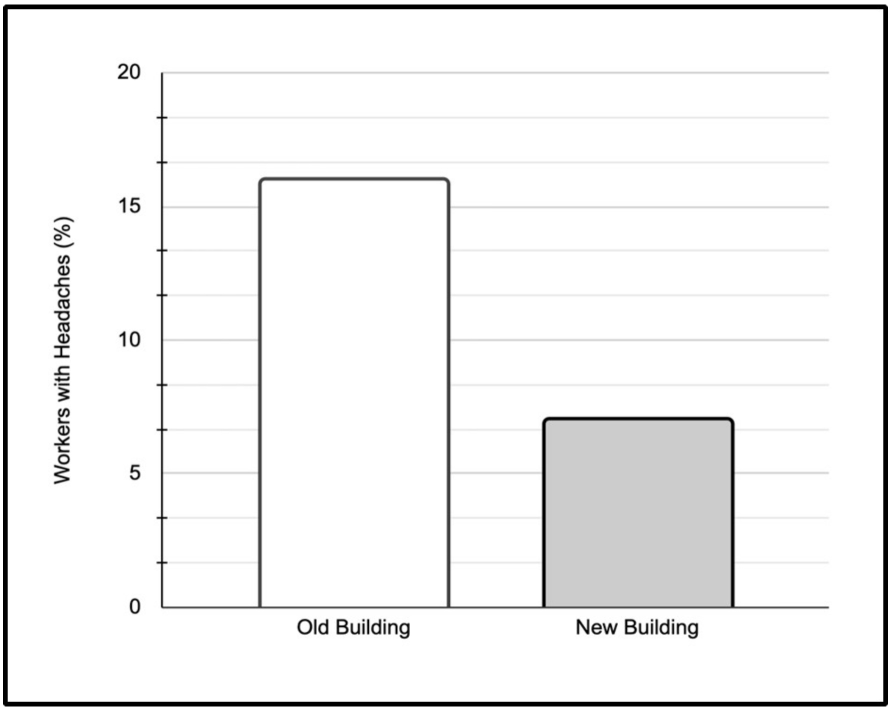

Figure 1. Headache incidence among officer workers (Old vs. New Building).

Table 2. Comparison of worker experiences in Old vs New buildings per survey results.

Aspects	Old Building	New Building	Change
Job Satisfaction	Lower	Higher	Positive (+)
Perception of Air Quality	Lower	Higher	Positive (+)
Temperature Conditions	Negative (Summer)	Negative (Still)	No Change
Noise	Negative	Negative	No Change

5. Conclusions and Recommendations

Diverse case studies have shown the effectiveness of sustainable solutions in mitigating heat stress among individuals and supporting the planet, with high accessibility for low-income countries. Widely adopted traditional methods used to decrease heat stress amongst the labor force are proven to harm individuals and are detrimental to the environment. While certain traditional methods yield limited effectiveness in decreasing heat stress for the long term, the high costs associated with these methods make them inaccessible, especially for developing countries.

Due to the limitations of traditional methods, it is recommended that countries adopt multiple sustainable methods to elevate both the short-term heat stress and the long-term environmental drawbacks. To avoid the extensive amount of investment that sustainable methods require, countries are advised to begin efforts with cost-effective traditional methods, such as work time shifts, and then implement the more costly sustainable methods.

The future of heat mitigation involves supporting sustainable methods. It is suggested that countries should prioritize the economic burden of heat-induced productivity loss and prioritize efforts to mitigate this issue. Countries are advised to implement favorable public policies that encourage the widespread adoption of sustainable heat-mitigation methods, specifically in industries with high carbon emission output. In terms of research, there is a notable gap in existing studies that explore the effectiveness of methods on the economy quantitatively due to complexity and other limitations. Future studies require more thorough research that analyzes economic impact with data in order to draw more informed suggestions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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