Identification, Classification, and Prioritization of Effective Factors in Producing Thermal Strain in Men at Workplaces using Fuzzy AHP Technique

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Abstract

Background: Various factors can affect thermal strain at workplaces. To prevent heat illnesses due to the heat strain, one must identify and prioritize these factors. Therefore, the present study was aimed to determine the relative importance of the effective factors in producing thermal strain in men at workplaces using fuzzy AHP technique. Materials and Methods: This qualitative practical study was performed in 2019. Effective factors in producing heat strain were identified by a literature review. Then, an expert panel reviewed the identified factors and omitted some of them. Further, the balance theory of job design was applied to classify the heat strain factors. Later, these factors were categorized into six groups, including environmental, personal, job, clothing, administrative, and lifestyle elements. In the end, the fuzzy analytical hierarchy technique was used for prioritizing the elements and factors involved in each of them. Results: Based on the results, the environmental element had the highest relative weight and priority (0.178). Other priorities were assigned to the job element (0.171), clothing element (0.171), personal element (0.169), administrative element (0.169), and lifestyle element (0.142), respectively. Conclusion: In general, the results showed that environmental factors are the most effective ones in producing heat strain. The results of the present study can be helpful in controlling the thermal strain.

Keywords: Fuzzy AHP, men, prioritization, thermal strain factors, workplaces

Introduction

There are many harmful agents in workplaces that threaten the health of the workers and can cause occupational illnesses and even death. Heat is one of the most important physical hazards in numerous environments of various industries such as steel, casting, metallurgy, petrochemicals, glassware, kitchens, bakery, mines, and agriculture. In addition, many countries, such as Iran, are located in arid and semiarid climate zones of the earth planet. More than 30% of the earth’s land is covered in arid and semiarid climate zones. Heat exposure can cause changes in the body’s physiological parameters such as increased heart rate, body temperature, skin temperature, and sweating rate, so-called thermal strain. If the thermal strain is not controlled, it can lead to illnesses and consequences such as headache, heat shock, heat fatigue, thermal syncope, heat loss, physical and mental impairment, neuropsychiatric symptoms, decreased consciousness and perception, and even death. According to Gubernot et al., thousands of workers suffer from heat-related illnesses, and over the past decade, 359 civilian workers have died due to heat exposure in their workplaces in the United States. The average fatality rate is 0.22 per 1 million workers. These statistics are not available in developing countries. However, the fatality rate related to the heat stress in these countries is certainly higher because of the old industrial equipment. In addition, it is a fact that the air...
temperature of the Earth is rising. Deschenes and Greenstone showed the effect of the climatic change on mortality in the United States. The results of their study indicated that increased temperatures from 2010 to 2019 can enhance the annual mortality rates by nearly 3%. In addition, heat exposure can reduce productivity and increase accidents in workplaces. To prevent thermal effects, the effective factors producing heat strain must be identified and prioritized, so that by controlling these factors, heat-related illnesses can be reduced. AHP, as a multicriteria decision-making method, was introduced by Saaty. AHP is applied to determine the relative importance or weight of the factors. In this method, the integrated opinions of experts are used for decision making and prioritizing. AHP describes criteria and subcriterions as a hierarchical structure and makes a pairwise comparison. However, the traditional hierarchy analysis method does not properly reflect human thought. The disadvantage of this method is the uncertainty and inaccuracy of comparisons since crisp numbers are used in the paired comparisons. Decision-makers are often unable to express their explicit opinion on the priority of the factors due to the fuzzy nature and the uncertainty of the comparisons. Therefore, the utilization of fuzzy logic in the AHP technique can solve this problem. The fuzzy analytical hierarchy process (FAHP) is a suitable method in the conditions of uncertainty and fuzziness. In this technique, experts are asked to compare the elements relative to each other and express the relative importance of them using linguistic words and fuzzy numbers.

Since no comprehensive studies on identification, classification, and prioritization of the effective factors in producing thermal strain have been carried out, this study was aimed to determine the relative importance of the effective factors in producing the thermal strain in men at workplaces using fuzzy AHP technique.

**Materials and Methods**

This qualitative practical study was performed in 2019. The procedure of the present study composed of three main steps as follows:

**Identifying effective factors on heat strain**

Effective factors in producing heat strain were identified by a literature review through search in the databases of Web of Science, PubMed, Scopus, Science Direct, Google Scholar, and Google using keywords including heat stress, heat strain, hot condition, warm condition, thermal environment, factors, and risk factors. Then, the identified literature was reviewed, and the factors were extracted. The factors such as clothing, personal, and environmental factors were used as the keywords for a second search. In addition, sixty heat stress assessment indices were studied, and their factors were extracted. In total, 111 factors were identified. In the next steps, the repetitive factors were eliminated and the physiological effect mechanisms of the residual factors on the changes of the core temperature, heart rate, skin temperature, and sweating rate were investigated. Later, a panel composed of four Iranian professors with research history on the heat stress reviewed the factors and their mechanism and omitted some of them. In the end, 41 factors remained.

**Classifying effective factors on heat strain**

According to the balance theory of job design, a working system is composed of five elements, including individual, environment, task, tools and technology, and organization. There should be interactions between these five elements to produce a stress load. This theory was applied to classify heat strain factors. Personal factors were considered as the individual element, environmental factors as the environment element, job factors as the task element, clothing factors as the tools and technology element, administrative factors as the organization element. Lifestyle was added to the five elements as a result of which heat strain factors were categorized into six groups.

**Prioritizing criteria and subcriterions using FAHP method**

The fuzzy hierarchical process was performed through the following steps:

**Constructing hierarchical structure**

The comprehension of a large problem by humans is a complicated and difficult task hence its various dimensions may not be considered. Therefore, with the decomposition of a large problem to the smaller elements, relationships, and concepts of the decision-making process can accurately be understood. The hierarchical structure tree created by this technique can help to understand and solve the problem. In the present study, based on the identified factors and their categorization, the goal, criteria, and subcriteria of the AHP model were specified and the hierarchical structure was constructed. Heat strain, elements, and factors of each element were considered as the goal, criteria, and subcriteria, respectively. This structure has been depicted in Figure 1.

**Selecting an expert panel for paired comparisons**

Seventeen Iranian and non-Iranian experts with the prominent research history in relation to heat stress, including seven professors, three associate professors, five assistant professors, and two Ph.D. candidates from occupational health engineering, environmental ergonomics and physiology, and physical activity departments conducted the paired comparisons in this study.

**Preparing AHP questionnaire**

In the AHP questionnaire, tables were separately designed for the paired comparison of the criteria and each group of the subcriteria. In total, seven tables were drawn. Experts in each comparison between two factors responded to a general question through the pairwise matrix in terms of a five-point Likert scale, i.e., which item is more important in creating thermal strain? The Likert scale consisted of equally important, weakly more important, strongly more important, very strongly more important, and extremely more important.
Defining fuzzy numbers
Chang (1996) developed an extended analysis method to implement an analytical hierarchical process using fuzzy logic. In this method, triangular fuzzy numbers are used to decrease uncertainties in paired comparisons. In the present study, triangular membership functions of fuzzy numbers were applied to calculate the weights gained from the expert opinions. Triangular fuzzy numbers (M) are defined using three crisp numbers between 0 and 1 as M = (l, m, u). Where, l, m, and u parameters represent the smallest possible value, the most promising value, and the largest possible value, respectively. Figure 2 depicts the membership functions of triangular numbers. Horizontal and vertical axes represent the degree of membership and the fuzzy number, respectively. The linguistic words of experts were converted to Triangular fuzzy numbers, as described in Table 2. The Fuzzy hierarchical process was performed based on their opinions.

Table 1: An instance of pairwise matrix between factors of A, B, and C

|       | Extremely more important | Much more important | More important | Slightly more important | Equally important | Slightly more important | More important | Much more important | Extremely more important |
|-------|--------------------------|--------------------|----------------|-------------------------|-------------------|-------------------------|----------------|-------------------|-------------------------|
| A     | 5                        | 4                  | 3              | 2                        | 1                 | 2                       | 3              | 4                 | 5                       |
| B     | 5                        | 4                  | 3              | 2                        | 1                 | 2                       | 3              | 4                 | 5                       |
| C     | 5                        | 4                  | 3              | 2                        | 1                 | 2                       | 3              | 4                 | 5                       |

Forming a paired comparison matrix (A) using fuzzy numbers
The paired comparison was performed by the decision matrix, as shown in equation 1. Fuzzy numbers of the paired matrix have been presented as $M_{ij}$. Subscripts of i and j indicate the numbers of the row and column, respectively.

$$
\tilde{A} = \begin{bmatrix}
1 & M_{12} & \cdots & M_{1n} \\
M_{21} & 1 & \cdots & M_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
M_{n1} & M_{n2} & \cdots & 1
\end{bmatrix}
$$

Calculating $S_i$
$S_i$ is a triangular fuzzy number related to the relative weight of each criterion or sub-criterion that is calculated by equation 2.

$$
S_i = \frac{\sum_{j=1}^{m} M_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij}}^{-1}
$$
In this equation, ∑ gi and include the column number, row number and fuzzy numbers of the paired matrix, respectively.

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} = \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} \right] \]

were computed by the following equations:

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} = \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} \right] \]

Calculating degree of possibilities
If \( S_1 = (l_1, m_1, u_1) \) and \( S_2 = (l_2, m_2, u_2) \) are two triangular fuzzy numbers, the degree of the possibility \( (\mu_{S_2}(d)) \) of \( S_2 \geq S_1 \) is defined by the following equation:

\[ V(S_2 \geq S_1) = hgt(S_2 \cap S_1) = \mu_{S_2}(d) = \begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_2 \geq u_2 \\ \frac{l_2 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \]

The degree of the possibility of a triangular fuzzy number relative to \( k \) triangular fuzzy numbers was obtained by the following equation:

\[ V(S_k \geq S_1, S_2, \ldots, S_k) = V[(S \geq S_1) \text{ and } (S \geq S_2) \text{ and } \ldots \text{ and } (S \geq S_k)] = \text{Min} V(S \geq S_i, i = 1, 2, 3 \ldots k) \]

Calculating weights of criteria and subcriteria
Equation 8 is used for the computation of the weight vector of the criteria and subcriteria in the paired matrix.

\[ d' (A_i) = \text{Min} V(S_i \geq S_k) k = 1.2 \ldots n, k \neq i \]

Therefore, the non-normal weight vector will be as follows:

\[ W = (d' (A_1), d' (A_2), \ldots, d' (A_n)) \]

Calculating normal weight
To calculate the normal weight, the weight vector gained from the previous step was normalized by equation 10.

\[ W = (d(A_1), d(A_2), \ldots, d(A_n)) \]

The geometric average was used to combine \( N \) comments of experts, as shown in equation 11. The output is a comparison matrix, as the result of the expert judgments.

\[ a_{ij} = \left( \prod_{k=1}^{K} A_{ik} \right)^{1/K} K = 1.2 \ldots K \]

Calculating consistency index
The consistency index (CI) was computed, using Gogus and Boucher method to ensure the reliability of the obtained results. The results showed that the consistency index of all matrices was less than 0.1. Therefore, the results were considered reliable.

Ethical approval
The study approved by the medical Ethics committee of Tehran University of Medical Sciences on March 11, 2019 (IR.TUMS. SPH.REC.1397.321).

Results
In the present study, the fuzzy AHP was applied to reveal the importance weight of each effective element and factor in
producing thermal strain. The consistency rate (CR) of this study was 0.063, which is appropriate. Table 3 presents the relative weight and prioritization of the elements. Based on the results, the environmental element had the highest relative weight and priority (0.178). Other priorities were assigned to job, clothing, personal, administrative, and lifestyle element, respectively. However, the importance of the clothing element was equal to that of the job element and the importance of the personal element was like that of the administrative one.

Table 4 illustrates the relative weight and prioritization of effective thermal strain factors.

| Environmental element | Factors                        | Relative weights | Priorities |
|------------------------|--------------------------------|------------------|------------|
| Air temperature        |                                | 0.128            | 4          |
| Relative humidity      |                                | 0.132            | 1          |
| Radiant heat           |                                | 0.130            | 2          |
| Conductive heat        |                                | 0.127            | 5          |
| Wind speed             |                                | 0.129            | 3          |
| Wind direction         |                                | 0.124            | 6          |
| Air pollution          |                                | 0.118            | 7          |
| Noise                  |                                | 0.110            | 8          |

| Personal element       | Age                            | 0.125            | 4          |
|                       | Body resistance                | 0.128            | 2          |
|                       | Skin color                    | 0.113            | 6          |
|                       | Aerobic capacity              | 0.128            | 2          |
|                       | Body mass index               | 0.127            | 3          |
|                       | Body surface area             | 0.124            | 5          |
|                       | Body fat percentage           | 0.125            | 4          |
|                       | Effective diseases            | 0.130            | 1          |

| Job element            | Metabolism                     | 0.286            | 1          |
|                       | Mental workload                | 0.222            | 4          |
|                       | Body movement                  | 0.260            | 2          |
|                       | Body posture                   | 0.233            | 3          |

| Administrative element | Heat adaptation planning       | 0.143            | 3          |
|                       | Duration of heat exposure      | 0.145            | 2          |
|                       | Work-rest cycle               | 0.143            | 3          |
|                       | Shift work                    | 0.138            | 5          |
|                       | Type of exposure              | 0.141            | 4          |
|                       | Control measures              | 0.145            | 2          |
|                       | Access to cooling facilities  | 0.146            | 1          |

| Lifestyle element      | Smoking                        | 0.189            | 4          |
|                       | Salt consumption              | 0.197            | 3          |
|                       | Drinking water                | 0.213            | 1          |
|                       | Sleep and rest situation      | 0.200            | 2          |
|                       | Work experience in a warm environment | 0.200 | 2          |

| Clothing element       | Material                       | 0.111            | 3          |
|                       | Size                           | 0.108            | 5          |
|                       | Type of weave                  | 0.110            | 4          |
|                       | Thickness                      | 0.112            | 2          |
|                       | Color                          | 0.108            | 5          |
|                       | Ventilation                    | 0.114            | 1          |
|                       | Use of underwear               | 0.111            | 3          |
|                       | Covered body surface area      | 0.112            | 2          |
|                       | Personal protective equipment  | 0.114            | 1          |

**Discussion**

In the present study, 41 effective factors in producing heat strain were identified and categorized into six groups, including environmental, personal, clothing, administrative, and lifestyle elements. Zheng et al. (2012) identified ten factors in three groups, including work, environment, and worker to evaluate safety in hot and humid environments. McLellan et al. (2013) introduced four main groups of variables affecting the heat balance, including the local environment, clothing, work intensity, and individual factors. In the present study, more effective factors were identified and classified into six groups based on the balance theory of job design.

The results of FAHP showed that environment, job, and clothing factors were the most effective variables in producing heat strain. It is important for human beings to keep the body core temperature within a narrow range around 37°C to provide comfort, good performance, and health. In total, there are main five factors influencing heat storage in the human body, including conductive heat, convective heat, radiant heat, sweat evaporation, and metabolism. The environment directly affects the first four factors. The warm and humid environment not only creates a difficult condition to lose heat through the convention and radiation mechanisms but also increases heat absorption. Therefore, the environment element plays a very important role in heat strain. In fact, the
main factors at many of the heat stress assessment indices such as Wet Bulb Global Temperature (WBGT) and Predicted Heat Stress (PHS) are the environmental factors. Even, some of the indices are only calculated based on these factors. Metabolism also is one of the demands of the job to produce heat in the body. In addition to the main five factors, clothing regulates the heat transfer between the human body and the environment. Other elements based on the priority included personal, administrative, and lifestyle factors, respectively. Personal factors determine the individual susceptibility, affecting heat absorption and dissipation processes while administrative and lifestyle elements control-imposed heat stress. Hence, it seems that the opinion of the experts is logical. Golbabaee et al. (2019) weighted three variables to assess the risk of heat stress, including task characteristics, working environment, and workers, using AHP and TOPSIS in a foundry shop. The results indicated that the working environment with the coefficient of 0.526 had the highest impact on the risk assessment process. The second important variable was the task characteristics with a coefficient of 0.279. Zheng et al. (2012) also used a trapezoidal fuzzy AHP method for the work safety evaluation in hot and humid environments. The weights of the environment, work, and worker were determined as 0.540, 0.297, and 0.163, respectively. Furthermore, the results of Dehghan et al. study (2015) demonstrated that the environmental variables of the heat strain score index (HSSI) had the highest correlations with the aural temperature and physiological strain index (PSI). These results are consistent with the results of the present study.

Of the environmental factors, the highest priorities were assigned to relative humidity, radiant heat, wind speed, air temperature, and conductive heat, respectively. In the WBGT index, as a valid heat stress assessment indicator, the wet-bulb temperature (0.7), global temperature (0.2), and dry bulb temperature (0.1) have greater weight, respectively. In addition, Liang et al. (2011) developed a new environmental heat stress index based on the experimental data and cox regression. The weights of the wet-bulb temperature and dry bulb temperature were calculated to equal to 0.62 and 0.38, respectively. These results show the high importance of the relative humidity and radiant heat than other parameters. Indeed, high environmental temperature makes a difficult situation to lose heat by convection and radiation mechanisms. While the high relative humidity decreases the ability of sweat evaporation from the skin and enhances the core temperature. The effect of wind depends on air temperature, in a way that if the air temperature is lower than the skin temperature, the wind reduces the heat strain, otherwise increases it. But, the radiant heat is independent of the wind speed and can directly and quickly affect thermal strain. Of course, the differences in weights of the five factors mentioned are not significant, which reveal their nearly equal importance.

Personal factors based on the priority include effective diseases, body resistance, aerobic capacity, body mass index, age, body fat percentage, body surface area, and skin color. Effective diseases such as respiratory, cardiovascular, diabetes, and hypertension disrupt the conservative mechanism against heat stress. Based on the results of a meta-analysis study (2007), odds ratio (OR) values of the heat-related death from pulmonary illness, cardiovascular illness, mental illness, use of psychotropic medications were equal to 1.61, 2.48, 3.61, and 1.90, respectively. In addition, the results of a review study performed by Kenny et al. (2010) revealed that the OR values of the heat-related death or hospital admission for diabetes and obesity were equal to 1.3 and 1.2, respectively. Furthermore, Fouillet et al. (2006) reported that the mortality ratio in France during the 2003 heatwave in Europe increased with age, from 1.3 to more than 1.7 for the aged people. The comparison of these ratios shows that effective diseases, overweight, and age play a more important role than other factors. Aerobic capacity is also another important factor. Viveiros et al. (2012) demonstrated that body thermoregulation is similar between young and middle-aged people with the same aerobic capacities. Therefore, increased risk of heat-related mortality in older people may be due to decreased aerobic capacity. These factors can help to identify the individuals who are at high-risk during the activity under heat. It is important to note that the stated factors can affect the thermal strain in all people of society and not just workers.

The factors of the job element based on the priority comprise physical activity, body movement, body posture, and mental workload. According to Zheng et al. (2012), the work intensity has the highest weight (0.540) among the work factors. In another study (2019), the weights of the work nature, work intensity, and work duration were calculated as 0.145, 0.616, 0.239, respectively. These results show that work intensity is the most effective factor in the job element. In addition, Body movement and body posture are other substantial factors. The results of Wang’s study (2017) demonstrated that body movement and body posture significantly affect the thermal exchange between the clothed manikin and the environment; the skin and core temperature of the standing manikin were greater than those of the walking manikin.

Of administrative factors, access to cooling facilities and control measures had the highest weights. Other factors based on the priorities consisted of the duration of heat exposure, work-rest cycle, heat adaptation planning, type of exposure, and shift work. The results of a review study revealed that the odds ratio values of the heat-related death for the factors of the working fan and air conditioning are equal to 0.71 and 0.2, respectively. In addition, in a meta-analysis study, the odds ratio values of the working fan and air conditioning were calculated as 0.60 and 0.23, respectively. These results show that access to cooling facilities and control measures can greatly reduce thermal strain. Other factors are related to time. Indeed, an organization can control the thermal strain of individuals by planning the time. The time planning in addition to the reduction of heat exposure can create heat adaptation. Good planning can make heat adaptation after 10 to 14 days.
Among lifestyle factors, drinking water and rest situation had the greatest weights, respectively. Drinking water replaces evaporated body water due to sweating under warm conditions. Dehydration greatly increases the core body temperature and has an adverse effect on physical and cognitive functions. For every 1% of weight loss due to dehydration, the temperature rises from 0.1 to 0.2°C and heat rate elevates from 3 to 5 beats per minute. [31] As a result, it enhances the risk of heat-related illness and occupational accidents. [32] Craig and Cummings observed that dehydration (weight loss from 2 to 4%) decreases the aerobic capacity (VO2 max) from 10 to 22%. [33] Therefore, drinking water during heat exposure is a great preventative factor. Sleep and rest, as another significant factor, also provide the recovery and improve the effect of heat exposure. Decreased sleep and rest can delay the recovery process.

Of the clothing factors, the personal protective equipment and ventilation were selected as the priority. Personal protective equipment, due to its properties to protect against chemicals, is often Impermeable, which disrupts the sweat evaporation process and thus results in thermal strain. [34] In addition, ventilation is related to air permeation. Clothing with less permeability provides less ventilation. Clothing ventilation allows the ambient air to circulate and move the stagnant air out of the microenvironment. Parsons reported that the relative air movement between the body and environment due to human movement and air velocity reduced the clothing thermal insulation from 0.8 to 0.6 clo. [35] Other factors based on the priority include thickness, covered body surface area, material, underwear, weave, size, and color.

**Conclusion**

In general, the results showed that environmental factors are the most effective factors in producing heat strain. Other factors, considering priority comprise job, clothing, personal, administrative, and lifestyle elements, respectively. However, the importance of the clothing factors was equal to that of job factors and the importance of personal factors was equal to that of administrative factors. Given the limitations, the results of the present study can be helpful in selecting solutions for controlling thermal strain. Therefore, it is recommended that employers provide the appropriate climatic conditions in workplaces. As well as, it is suggested that they decrease the job pressure and improve the clothing properties of workers. If the implementation of these solutions is not possible, it is proposed that they apply the administrative measures and select workers based on the personal properties in warm workplaces. The lifestyle of workers can also be useful in reducing heat strain.

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**Conflicts of interest**

The authors declare that they have no conflict of interest.

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Yazdanirad, et al.: Prioritization of effective thermal strain factors

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