Wearable Sensing Devices and the Internet of Things for Worker Safety and Health Management in the Steel Manufacturing Industry

Hazards are ever-present in the steel plant environment, and a heightened awareness and emphasis on safety is a necessary priority for our industry. This monthly column, coordinated by members of the AIST Safety & Health Technology Committee, focuses on procedures and practices to promote a safe working environment for everyone.

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The steel manufacturing industry is one of the most hazardous industrial sectors characterized by a wide range of risks and extreme working conditions that could cause injury, illness or fatalities to employees. These extreme workplace conditions can result in poor productivity and safety performance.[1] Through the effective identification of environmental conditions that can lead to worker injury, illness or fatality, safety and production managers can anticipate and mitigate working conditions that could reduce safety performance and productivity.[2,3] More improvements in safety and health management in steel manufacturing can be achieved by deploying emerging technologies such as wearable sensing devices (WSD) and the Internet of Things (IoT) to detect potential hazards, sense dangerous working conditions, and provide warning alerts to workers to predict and prevent illnesses, injuries or fatalities.

Deploying emerging safety technologies for proactive and active monitoring can provide an additional layer of protection to workers in the steel manufacturing industry. Studies indicate that wearable sensing devices based on the Internet of Things (IoT-based WSDs) have the potential to improve worker safety by proactively sensing hazards in the work environment and providing real-time information about safety and health risks to personnel.[4–7] IoT-based WSDs can be used to acquire data, analyze the data and immediately deliver personalized information to workers and safety personnel so that appropriate actions can be taken to prevent issues in high-risk workplaces. Using such emerging technologies can bring about a procedure for continuous monitoring, measuring and improvement of safety and health performance in steel manufacturing plants.

Various sensors can be used to continuously monitor workers' safety and health metrics such as skin temperature, heart rate, body posture, body balance, and working conditions including radiation levels, noise or toxic gases. In addition, multiple sensors can be integrated to simultaneously collect and analyze several metrics to create great possibilities for effective management of workers' safety and health behaviors and conditions in steel manufacturing plants. These IoT-based WSDs could come in the form of wrist bands, wristwatches, or integrated into personal protective equipment (PPE) such as safety gloves, safety glasses, safety vests, safety helmets and smart shoes. This article reports an evaluation of the applications of IoT-based WSDs for worker safety and health management in the steel manufacturing industry. It is anticipated that the implementation of these emerging safety technologies will reduce injuries and illnesses, thereby improving safety and health performance and productivity in the steel manufacturing industry.

Wearable Internet of Things for Safety and Health Monitoring in Steel Manufacturing

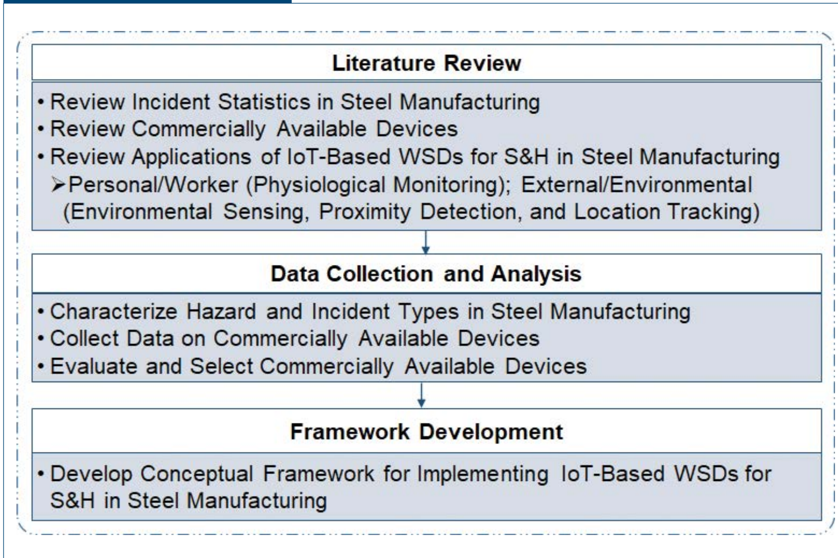
Wearable electronics are devices that can be worn by humans to continuously and closely monitor an individual's activities, without interrupting or limiting the user's motions.[8,9] The most commonly used wearable sensors include wearable body temperature sensors, pulse and blood oxygen level sensors, accelerometers for motion sensing, airflow sensors, electrocardiograms, and galvanic skin response sensors.[10,11] The incorporation of computer and electronic technologies into clothing and other accessories in wearable devices gives them unique capabilities and opens up great potential for various applications in industrial work environments. Based on the distinctive functions performed and applications in different sectors, these wearable devices have the potential to positively impact the safety and health performance of workers in any hazardous industrial work environment. These sensors and systems are capable of detecting, monitoring and tracking both personal and environmental properties or data that can be used for workers' safety management in high-risk work environments typified by steel manufacturing plants.

Existing studies indicate that wearable Internet of Things (WIoT) devices can be deployed in a wide range of applications in industrial sectors which can be broadly categorized as physiological monitoring, environmental sensing, proximity detection and location tracking.[5,12,13] With these applications, IoT-based WSDs can be used to monitor, sense, track and detect a wide range of workplace hazards and vital signals, which can provide early warning signs of safety and health issues to workers. The different types of safety and health hazards in steel manufacturing work environments make these applications relevant in the management of workers' safety and health in steel manufacturing. The recent growth in the popularity of interconnected wearable devices with sensing, computing and communication capability has been very rapid, leading to the emergence of different types of WIoT devices. Despite the widespread use of these devices in sectors such as healthcare, sports and fitness, high-risk industrial sectors such as the steel industry, which can directly benefit from the potentials of these devices, are yet to start taking advantage of these benefits. Given the recent development, there is a need to investigate how this category of emerging technologies can be implemented for safety and health management in the steel manufacturing industry.

Technology Selection Process

Since the process of selecting technology is usually characterized by uncertainty, complexity, multiple stakeholders and numerous objectives, it is often modeled as a multi-criteria decision-making (MCDM) problem which entails the evaluation of a set of alternatives and taking into account a set of decision criteria.[14–16] MCDM is the process of making decisions between several alternatives by defining the decision criteria and their weights. The procedure enables the determination of the optimal choice among a set of options over a set of multiple criteria.[17] The process leads to the ranking of alternatives, from the most to the least favorable, thus allowing comparison of alternatives.[18] The technique for order preference by similarity to ideal solution (TOPSIS) is based on the concept that the chosen alternative should have the shortest distance from the ideal solution and the farthest from the negative ideal solution can be used to identify the best alternative quickly. In addition, the TOPSIS method requires a limited amount of subjective input and it is applicable to both qualitative and quantitative data.

Figure 1



Research process.

Table 1

Sample Characterization of Hazards in the Mini-Mill Steelmaking Process

Work process	Hazard type	Safety hazards	Health hazards	Potential illness/ injury/accident	Metric	Function
Electric arc furnace	Materials	Explosives; spills and sparks; molten metal; flying objects	Molten metal; toxic gases/chemicals; flying objects	Respiratory illness/ lung damage; acute and chronic poisoning; heatstroke; heat stress; acoustic trauma; hearing loss/ impairment	Body temperature; respiratory rate; heart rate; blood pressure; ambient temperature; noise level	Physiological monitoring; environmental sensing
	Equipment/tools	Struck by/caught in/ between moving machinery; electrocution; Falling objects	Unguarded equipment/ tools; flashes and glare; sharp/blunt tools; electrocution			
	Work environment	Spills and sparks; toxic gases; falling object; fire; poor housekeeping; loud noise	Toxic gases/chemicals; high ambient temperature; loud noise	Eye damage; hearing loss; skin rashes; severe burns; struck by transporting molten metal; crushed by moving machinery; explosion	Light intensity; proximity detection; worker location tracking	Proximity detection; environmental sensing; location tracking
	People/human error	Proximity to furnace; not wearing appropriate PPE; poor housekeeping; unauthorized entry; bad worker posture	Proximity to furnace; not wearing appropriate PPE; poor housekeeping; unauthorized entry			

Research Approach

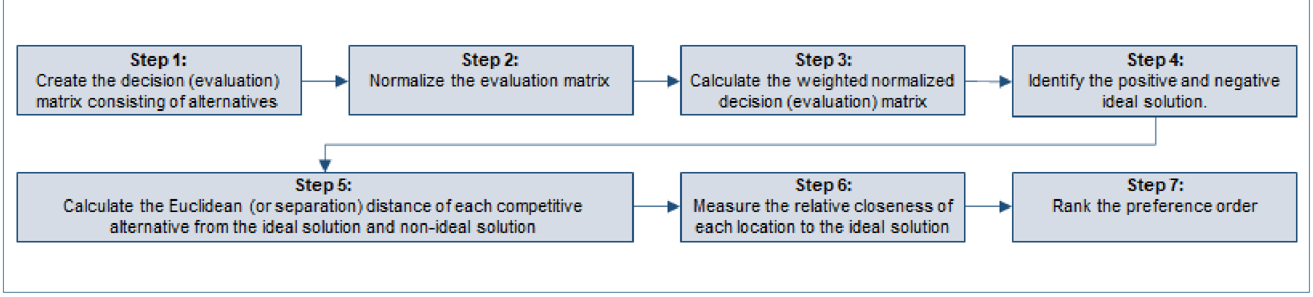
This study was conducted using a combination of tasks shown in Fig. 1. First, reports of incident statistics in steel manufacturing were reviewed to identify the trends of fatal and non-fatal injuries in the primary metal manufacturing industry and steel manufacturing.

Thereafter, research and industry findings on the applications of IoT-based WSDs in other industrial sectors were reviewed and used to synthesize their potential applications for safety and health monitoring in steel manufacturing plants. These applications were evaluated by steel industry experts to ensure that they are reflective of the types of functions the devices are meant to perform in steel manufacturing. Following the process, a characterization of the safety and health hazards together with associated potential injuries, illnesses and accidents was conducted. In the characterization, the hazards and incidents were connected to measurable metrics and IoT-based WSDs applications. The evaluation of commercially available IoT-based WSDs phase of the study was conducted in two steps which were the search for applicable commercially available IoT-based WSDs and then the evaluation of the devices using a decision-making process to select those that can be used for safety and health monitoring in steel manufacturing. Based on the findings of the processes and review of technology implementation frameworks developed across different industrial sectors, a conceptual framework was developed for the initial implementation of IoT-based WSDs for safety and health monitoring in steel manufacturing.

Results and Discussion

Characterization of Safety and Health Hazards in Steel Manufacturing — The effective management of safety in

Figure 2



Technique for order preference by similarity to ideal solution TOPSIS process for evaluating commercially available wearable sensing devices based on the Internet of Things IoT-based WSDs .

Table 2

Definition of Linguistic Values for Evaluation Criteria

Linguistic values	Functions (No.)	Metrics (No.)	Prev. IIA (No.)	Price ($)	Device type	Alert methods	Volume (cm^3)	Weight (g)	Power source	Battery life (day)
VH = 4	4	4	4	0–50	PPE Integrated	4	0–50	0–50	Energy harvesting and storage	≥7.00
H = 3	3	3	3	51-200	Wristwatch/ armband	3	51-100	51-100	Renewable energy	4.00–6.99
M = 2	2	2	2	201-350	Clip/tag	2	101-200	101-200	Rechargeable battery	2.00–3.99
L = 1	1	1	1	351-500	Handheld	1	201-350	201-350	Non-rechargeable battery	0.25–1.99
M = 2	0	0	0	≥501	Unwearable	0	≥351	≥351	Power plug	≤0.25

VH (Very High); H (High); M (Medium); L (Low); VL (Very Low)

any industry requires a good understanding of the nature of hazards common to that industry.[19] The choice and implementation of specific measures for preventing workplace injuries, illnesses and fatalities in the iron and steel industry workforce depend on the recognition of the principal hazards, and the anticipated injuries, ill health/diseases or accidents.[1] In order to characterize the different types of hazards associated with steel manufacturing, there is a need to understand the types of work tasks or activities that make up the steel milling process adopted for manufacturing steel products.

The research team used the mini-mill steelmaking process for the characterization of the hazards workers are exposed to in steel plants. As opposed to the integrated steel mills, which make new steel from iron ore in a blast furnace, most of the world's largest steel producers use mini-mills, in which most of the iron used is obtained from scrap steel, recycled from used automobiles and equipment or byproducts of manufacturing. Mini-mills melt and refine scrap steel using electric arc furnace (EAF) technology. The mini-mill steel production process has several stages. The process starts with the shredder which shreds the materials and separates ferrous from non-ferrous scraps. Ferrous scrap is refined and melted in the EAF, after which the molten steel is often further refined in a ladle metallurgical station.

The steel is then shaped in the continuous caster into semi-finished products such as billets, blooms or slabs. These semi-finished products are then further processed in the rolling mill into finished products using methods such as annealing, hot forming, cold rolling, pickling, galvanizing, coating or painting. The process ends with the finishing and transportation stage in which the products are cooled, sheared, bent or straightened as required, and then transported to the site or fabrication shop.

To characterize the hazards, the research team reviewed reports of steel manufacturing plants that use the mini-mill steelmaking process, studied/watched the AIST Steel Wheel, watched several videos of the mini-mill steelmaking process and culminated the entire activities with a tour of a steel mill in Texas, USA. The research team conducted an in-depth evaluation of the broadly classified hazards to categorize them based on how they can be proactively detected, tracked or monitored using IoT-based WSDs to provide early warning alerts to workers for predicting and preventing injuries, illnesses and

Table 3

Ranking of Evaluated Commercially Available IoT-Based WSDs

Device name	Device ID	Si+	Si-	Pi	Rank
Fitbit Sense	D12	0.04865	0.12290	0.7164	1
M3SAFE	D7	0.04818	0.11950	0.7127	2
Versa 3	D8	0.09185	0.07893	0.4622	3
Blackline Safety's G7c	D3	0.10419	0.08193	0.4402	4
Atmotube PLUS	D2	0.09188	0.07200	0.4394	5
Galaxy Watch3	D10	0.08848	0.06757	0.4330	6
Apple Watch Series 6	D9	0.09443	0.07197	0.4325	7
AirBeam2	D11	0.10340	0.05806	0.3596	8
Temp Stick	D5	0.11369	0.05489	0.3256	9
HAVwear	D4	0.12713	0.04213	0.2489	10
Honeywell BW™ Ultra	D6	0.12963	0.03265	0.2012	11
Embr Wave	D1	0.14095	0.03159	0.1831	12

Separation from ideal solution (Si+)
Separation from non-ideal solution (Si-)
Performance score (Pi)

fatalities. Practitioners in the steel manufacturing industry and safety researchers validated the spreadsheet containing the identified safety and health hazards. An excerpt from the spreadsheet containing the characterization of the safety and health hazards in steel manufacturing is shown in Table 1. This model is adaptable and can be used to characterize hazards associated with other types of steelmaking processes.

Evaluation of Commercially Available IoT-Based WSDs — In the search for commercially available IoT-based WSDs that can be deployed for workers' safety and health monitoring in steel manufacturing, a total of 40 different devices were obtained. Out of these devices, only 12 had complete data/information on 10 out of the 15 criteria proposed for evaluating the devices.

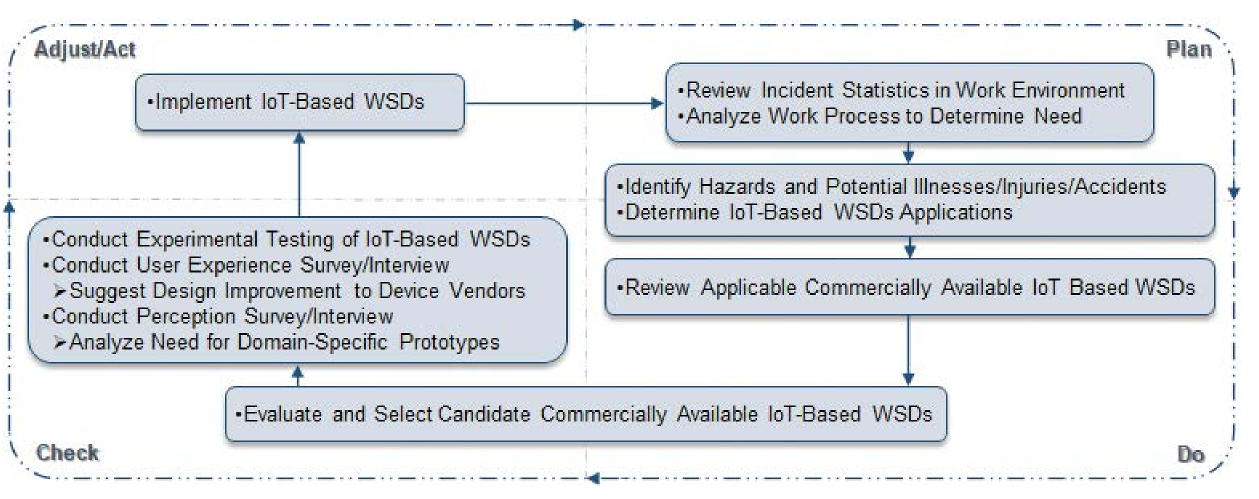
These 12 devices were then considered in the evaluation of commercially available IoT-based WSDs for the selection of the best alternatives for application in steel manufacturing. The TOPSIS process used for the evaluation and selection of the best commercially available IoT-based WSDs is depicted in Fig. 2. The use of this multi-criteria decision-making process is expected to support stakeholders in making decisions on suitable IoT-based WSDs to implement for workers' safety and health improvement in steel manufacturing. The linguistic values with five options (Very High (VH), High (H), Medium (M), Low (L), and Very Low (VL)) used to define each criterion for all the alternatives based on the data collected are presented in Table 2 while the final results of the TOPSIS process containing the ranking of evaluated commercially available IoT-based WSDs are shown in Table 3.

The final ranking of preferences in descending order as determined using this MCDM process allows the comparison of the relative performances of the different commercially available IoT-based WSDs. From the results of this TOPSIS process, Fitbit Sense (D12), M3SAFE (D7) and Fitbit Versa 3 (D8) emerged as the top three IoT-based WSDs and obtained the highest relative closeness to ideal solution values of 0.7164, 0.7127 and 0.4622, respectively. Hence, this MCDM process has identified Fitbit Sense, M3SAFE, and Fitbit Versa 3 as the best commercially available IoT-based WSDs among the considered devices that can be deployed for safety and health monitoring in steel manufacturing.

Conceptual Framework for Implementing IoT-Based WSDs in the Steel Manufacturing Industry — Due to the emerging nature of the application of IoT-based WSDs in industrial sectors, the initial implementation (expected to engender the rapid and strategic application) of this class of technologies can be modeled as an iterative design and management approach that can be used for the control and continuous improvement of the process.

As illustrated in Fig. 3, the plan–do–check–adjust/act (PDCA) model is used to develop a conceptual model for the initial implementation of IoT-based WSDs for worker safety and health monitoring in steel manufacturing. This approach suggests that the entire process starts with a plan that involves understanding, defining and analyzing the hazards and incidents associated with the steel manufacturing work environments and developing an action plan to

Figure 3



Methodology for implementing IoT-based WSDs in steel manufacturing industry.

mitigate or remove the problems (i.e., hazards and incidents) through the application of IoT-based WSDs for proactive and active safety and health monitoring. The "do" part of the model involves implementing the solution, identifying associated hazards and potential illnesses, injuries or accidents and determining IoT-based WSDs applications. The information is then used to conduct a review/search of applicable commercially available IoT-based WSDs which will then be evaluated to select candidate devices that can be tested at this initial implementation stage.

The criteria used in the evaluation and selection of devices will be used to inform the experimental testing that will be conducted in the "check" step of the framework. This testing will be accompanied by a user experience survey to gather information and feedback on the functionality and effectiveness of the devices which can further provide suggestions for improvements to device vendors. A perception survey will also be conducted at this stage to evaluate the views of a broader group of users and potential users at different levels of an organization or industry on the factors that can influence initial and full implementation. This is very important because it considers the attributes of personnel and organizational structures with strong potential to support successful implementation.

The need for domain-specific devices will also be analyzed at this stage. Existing studies on the implementation of innovative technologies across various industrial sectors reveal that different factors influence their successful implementation[20–22] and a few studies have particularly highlighted the need to evaluate issues associated with the privacy and security of data, and their impact on the implementation of IoT-based WSDs.[13,23] Based on the findings of the tasks in the previous stages, the IoT-based WSDs are initially implemented in the "adjust/act" stage of the framework.

Conclusions

The effective management of major hazards in any high-risk work environment requires proactive and active risk management strategies. With this class of technologies, objective and accurate data collection and analysis can be performed in order to provide real-time feedback for improving safety and health management in steel manufacturing plants. The results of this study will be beneficial to the steel manufacturing industry in several ways to primarily ensure the effective implementation of emerging safety technologies to enhance workers' safety and health management in the steel manufacturing industry.

First, the findings of this study provided unique information and insights that can be used to successfully implement proactive and active safety and health management strategies for the reduction and prevention of injuries, illnesses and accidents in steel manufacturing work environments. For instance, the characterization and mapping of hazards and potential incidents with IoT-based WSD application provide a novel approach for tackling worker safety and health problems from the first principle. This characterization and mapping model can be scaled and applied to varied types of work processes for the effective management of workers' safety and health in the steel manufacturing industry.

The MCDM technique used to model the technology selection process also provides a methodical approach through which steel industry stakeholders can evaluate available new technological devices and make informed decisions on those to select for implementation. The conceptual framework developed in this study provides an integrated approach to the evaluation of the initial implementation of IoT-based WSDs for worker safety and health management in the steel manufacturing industry. Furthermore, the findings of this study and the conceptual framework developed can be used to inform future studies geared toward ensuring the successful implementation of this class of technologies in the steel manufacturing industry.

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