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# Improving worker health and safety in wire arc additive manufacturing: A graph-based approach

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ABSTRACT

Research on human health and safety impacts of wire arc additive manufacturing is often overshadowed by the need for weld quality and mechanical strength improvements. To address this gap, a review of research literature is conducted focusing on the influence of welding process parameters, welding fumes, and fume exposure on worker health. The review uses a causal graph to classify research literature into two domains: manufacturing technology and public health. The graph serves as a precursor to development of a Bayesian network model, whose expected benefits, steps for implementation, and likely challenges that would be encountered during implementation are discussed.



## 1. Introduction

Despite the confluence of new trends and technologies in manufacturing, the workforce remains pivotal in driving innovation and productivity. New advancements, such as those introduced by Industry 4.0, portend to be of great benefit to the dynamic workforce of the future. In particular, adaptive management cultures will ensure safe working environments that deliver broad societal and economic benefits. The rapid development of technology, coupled with reduced timelines for technology assimilation, makes it a challenge to perform holistic evaluation of related worker health and safety impacts. Production risk and reliability assessments often overshadow worker health and safety evaluations due to increasing demand for quick, seamless integration of new technologies on the shop floor. Existing safety procedures, such as those prescribed by the U.S. Occupational Safety and Health Administration (OSHA), are effective in reducing worker accidents and injuries (OSHA, 1970). However, the disruptive nature of advanced manufacturing technologies, such as additive manufacturing (AM), requires extensive characterization of emissions and wastes that can increase safety and health risks to operators and others. Further, characterizing worker health and safety requires expertise in manufacturing processes, and also delves into domains such as measurement science, environmental science, and public health and safety.

Metal AM systems operate as multi-physical-chemical-metallurgical processes, with myriad interrelated parameters that must be characterized to understand their functionality. Mapping the interrelationships between process variables (parameters), their influence on process emissions and waste, and associated worker impacts is crucial for making informed decisions on the safety equipment and procedures required by emerging metal AM technologies. Integration of pre-existing knowledge (e.g., models and expert knowledge) can hasten the development of meta-models for process characterization.

A causal graph-based approach is presented in this research as means for integrating pre-existing knowledge in modelling AM-related worker health and safety impacts. Operator safety in a directed energy deposition process, wire and arc additive manufacturing (WAAM), is discussed as an application case. Implementation of a Bayesian network (BN) that integrates process knowledge (process operation, emissions, and related impacts), worker habits and exposure pathways, health and safety factors (health risks and severity of risks), and suitable safety protocols from the developed causal graph is discussed. Simulation results using the developed BN could be used to evaluate potential health risks associated with WAAM and to prescribe potential corrective/preventative measures.

The remainder of the manuscript is organized as follows: Section 2 discusses literature reporting emissions and health risks associated with the WAAM process; Section 3 discusses development of the causal graph representing the factors and interconnections as well as possible BN implementation; and Section 4 dis-

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**Nomenclature**

| | |
|---|---|
| BMC | blood mineral content |
| C.Filler | composition of filler weld |
| C.Fume | composition of fume |
| C.sgas | composition of shielding gas |
| CFE | cumulative fume exposure |
| $d$ | filler wire diameter |
| FC | fume concentration in working space |
| FGR | fume generation rate |
| HI | heat input |
| $I$ | arc current |
| $P$ | arc power |
| PPY | packs per year |
| SGFR | shielding gas flow rate |
| $t_{\text{exp}}$ | exposure time |
| $v$ | welding speed |
| $V$ | arc voltage |
| WFR | wire feed rate |

cusses the findings of the presented work and opportunities for future research.

## 2. Background

AM processes can produce 3D objects in a layer-by-layer fashion using polymers, metals, and ceramics. The advantages provided by AM in terms of unhindered design freedom, higher material efficiency, faster product realization, and less constrained supply chain have accelerated the adoption of AM in high value industries such as medicine, automotive, and aerospace (Bourell et al., 2000). With the increased adoption of polymer and metal AM technologies in mainstream manufacturing, studies must be conducted to evaluate the potential health impact of operators exposed to emissions and other risks.

Stefaniak et al. (2019) explored the operator health impact of emissions and exposures from industrial scale machines for material extrusion and material jetting based AM technologies. They found that the emission rate for both technologies were in the range of $10^9$–$10^{11}$ particles per minute, with particle sizes predominantly below 300 nm. They concluded that exposure to released particles is prevalent in AM work settings, but that total exposure must take into consideration other contributing factors, such as pre- and post-processing activities. The health impacts from exposure to particle/vapor emissions were not studied, but it was reported that the inhalation of emissions from ABS filament could result in asthma in operators and hypertension in rodents. The authors suggested that evaluation of potential emission points in industrial-scale AM machines is required to adequately measure heavy metal and volatile organic compound (VOC) exposure levels.

Similarly, Graff et al. (2017) characterized the presence of nanosized metal particles during metal AM. They studied different measurement techniques to characterize particles based on the number of particles, masses, sizes, and identities, focusing on alloys containing chromium, nickel, and cobalt. They found that a range of nanoparticles were present in the AM work environment. Specifically, exposure was greater for workers who directly handle metal powders. They suggested that improved material handling and measurement techniques for nanoparticles is essential; their development could provide useful knowledge that can be translated into workplace safety.

There is lack of information on emissions and related health impacts due to the infancy of WAAM technology and its mainstream use. However, WAAM functions similar to robot-assisted electric arc welding, wherein the arc is used as a power source to melt filler metal wire onto a substrate. The arc welding process is modified to produce welds that overlap one another in the form of layers to build a 3D metal product. Thus, emissions from WAAM and their associated health impacts are similar to those of traditional welding processes.

Koh et al. (2015) measured the exposure of Korean shipyard welders to welding fumes and evaluated the potential of fume exposure to lead to chronic obstructive pulmonary disease (COPD). They studied 240 male subjects with an average age of 48 and exposure duration of 15 years. The study subjects' smoking habits, occupational history, and medical history were used to determine the number of packs per year (PPY) of cigarettes smoked and cumulative fume exposure (CFE). They found average fume exposure was 7.7 mg/m$^3$-years, and reported a statistically significant excess risk of COPD for intermediate and high exposure groups. However, the authors concluded that a longitudinal study with more test subjects was required to confirm a causal relationship between welding fume exposure and risk of COPD.

Li et al. (2004) studied the effects of welding fumes on welders working in a vehicle manufacturing facility by using workers from a nearby food manufacturer as control subjects. It was found that welders had 4.3- and 1.9-times greater serum levels of manganese and iron, respectively, in comparison to the food industry workers. Based on linear regression analysis, no relation was found between the presence of the heavy metals in the blood with the age of the subjects. Of the 500 welders at the facility, thirty-seven who had frequent exposure to fumes from electric arc welding were selected for the study. The study included 22 males and 15 females in the age group of 38$\pm$1.5 years, who worked 7–8 h shifts per day. Among the bodily fluid samples that were collected were 24-h urine specimens and blood samples. In addition, air samples from the breathing zone of the welding space were collected. Conclusions from the study reflected upon higher concentrations of manganese (above prescribed safety regulations) in the work atmosphere, and long-term, low-level exposure to fumes inducing oxidative stress in the welders.

Sjögren and Ulfvarson (1985) studied respiratory symptoms and pulmonary functions among aluminum, stainless steel, and railroad industry welders. Non-welding industrial and railroad workers were included in the study as referents. The study found that welders exhibited a higher frequency of chronic bronchitis symptoms than their respective referents. The authors reported that 80% of chromium concentration measurements exceeded the Swedish occupational exposure limit of 20 $\mu$g/m$^3$ for hexavalent chromium in stainless steel welding, resulting in respiratory symptoms. More than 50% of ozone concentration measurements were above the allowable limit of 0.1 ppm for aluminum welders. However, pulmonary function did not appear to be affected for the welding group. The authors mentioned that smoking habits affected the frequency of chronic bronchitis more than welding.

A related study was conducted to investigate prevalence of respiratory symptoms, impairment of lung function, and occurrence of pulmonary radiography findings in 157 electric arc welders and 108 control subjects (Antti-Poika et al., 1977). In addition, air quality measurements were taken in the work environment for 88 of the welders. They found welders had simple chronic bronchitis more often than the unexposed workers (all men). However, no significant difference was found when accounting for time and level of exposure. In addition, no significant findings were reported for impairment of lung function or for pulmonary radiography measurements for all test and control subjects.

Saito et al. (2000) experimentally measured and verified the presence of hazardous welding fumes in the breathing zone of welders for a $CO_2$ shielded arc welding process. They used a welding robot and three kinds of welding wires. Shielding gas flow

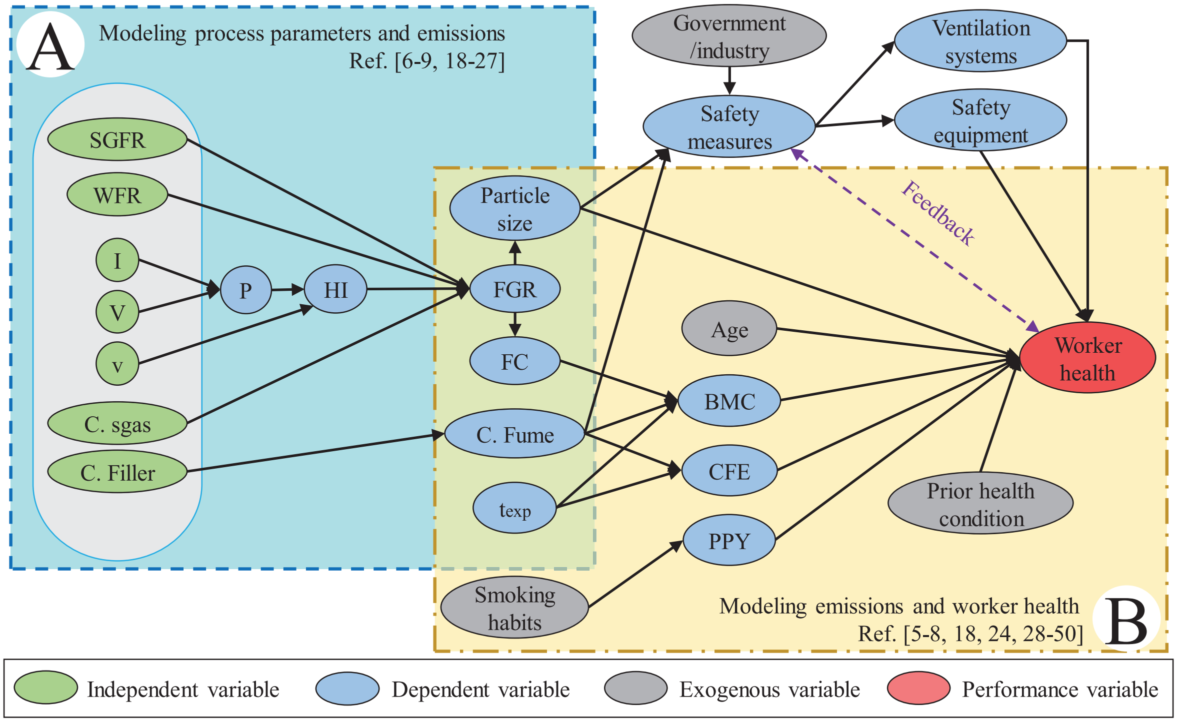


**Fig. 1.** Causal model of operator health impacts in wire arc additive manufacturing.

rate and the welding current were fixed at constant values. Experiments were conducted without local exhaust ventilation. Gas concentrations, fume concentrations, and particle size distributions were measured. Sampling involved synchronously moving and collecting data along a 200 mm horizontal and 300 mm vertical distance from the moving arc (the effective breathing zone for manual metal arc welding). It was found that fumes exceeded safe levels prescribed by safety standards; using half-face masks for protection was deemed to be insufficient. The authors suggested that use of supplied air respirators and/or use of half-face dust respirators along with a local exhaust ventilation system would be required to handle emission concentrations.

Popović et al. (2014) explored the influence of two types of filler materials, i.e., metal-covered wire and self-shielded wire, on the emission of toxic substances. They were able to detect and quantify the concentrations of dust, $CO_2$, CO, SO, Mn, Al, Ni, Cr, Cr (VI), Ca, and P. It was found that the concentrations of Mn and CO were high for metal-covered wires, while concentrations of P and Al were high for self-shielded wires. They suggested that the chemical composition of the shielding gas, filler material, and base metal determines the amount and composition of the welding fumes. These welding fumes are typically metal oxides formed when vaporized metal condenses rapidly on exposure to air. Other studies (i.e., Pires et al., 2006; Yoon and Kim, 2003) have established causality between fume generation rate and welding parameters such as electric current, arc voltage, wire diameter, shielding gas flow rate, welding speed, and the type of welding process (steady current or pulsed current welding). Welding fumes range from independent spherical particles less than 20 nm to conglomerated particles greater than 20 nm. Prior studies evaluated the health effects of short and long-term exposure to elemental metals in welding fumes, as shown in Table 1.

From the background literature study, we can infer that the body of research for modeling worker safety in welding falls into two domains: manufacturing technology (process) and public health. Findings from existing literature has been represented as a graph (Fig. 1) that indicates the causal relationships between different variables in the process domain and in the public health domain.

The developed causal graph can be combined with a Bayesian inference system to predict the effects of individual variables on worker health and safety measures. Section 3 describes the developed causal graph model and discusses the requirements and challenges for the development and implementation of a Bayesian network.

## 3. Causal modeling of worker health impacts in WAAM

The background study reported in Section 2 is used to develop a graph-based model for worker health in WAAM. The developed graph-based model enables visualization of the potential cause-effect relationships and correlations between the different variables of the system based on the referenced literature, as shown in Fig. 1. At this stage, some of the relations can be considered to be causal, especially in area A, while in area B more efforts are needed to validate the causality of elements. This causal graph provides a unified structure to integrate the knowledge from the two identified domains. In the manufacturing technology domain, research has focused on characterizing the influence of the process and parameters on generation of emissions/fumes (Li et al., . 2004; Sjögren and Ulfvarson, 1985; Antti-Poika et al., 1977; Saito et al., 2000; Jafari and Assari, 2004; Yu, 2001; Cole et al., 2007; Niemelä et al., 2001; Balkhyour and Goknil, 2010; Alfaro and Cayo, 2012; Topham et al., 2010; Yu et al., 2003; Heung et al., 2007; Keane et al., 2016). The public health domain has focused on characterizing the influence of emissions and components on worker health (Koh et al., 2015; Li et al., 2004; Sjögren and Ulfvarson, 1985; Antti-Poika et al., 1977; Jafari and Assari, 2004; Topham et al., 2010; Gube et al., 2013; Rongo et al., 2004; Hammond et al., 2005; Chinn et al., 1995; Cotes et al., 1989; Jayawardana and Abeysena, 2009; Bradshaw et al., 1998; Stănescu et al., 1967; Nakadate et al., 1998; Luo et al., 2009; Sharifian et al., 2011; Wang et al., 1994; Fogh et

**Table 1**
Effects of near and long-term exposure to welding fumes.

| Fume component | Effects of long-term exposure | Immediate symptom(s) |
|---|---|---|
| Manganese(Mn) | Affects the central nervous system with symptoms similar to Parkinson's disease (Hamai and Bondy, 2004) | Chills and fever, dryness of throat, weakness and aching of head and body |
| Hexavalent chromium(Cr (VI)) | Human carcinogen (specific to lungs) linked to DNA damage in welders (NTP (National Toxicology Program); Sellappa et al., 2010) | – |
| Nickel(Ni) | Linked to cancer of paranasal sinuses and lungs (List of Classifications – IARC Monographs on the Identification of Carcinogenic Hazards to Humans) | Itching pain, inflammation, redness |
| Aluminum(Al) | Associated with Alzheimer's disease (Kawahara and Kato-Negishi, 2011) | – |
| Phosphorous(P) | Linked to anemia, cachexia, necrosis of bone (Popović et al., 2014) | Abdominal pain, irritation to respiratory tract and eyes |

al., 1969; Storaas et al., 2015; Qin et al., 2014; El-Zein et al., 2003; Nemery, 1990; Hjortsberg et al., 1992; McCormick et al., 2008; McMillan and Pethybridge, 1983; Barhad et al., 1975; Kilburn et al., 1989; Mur et al., 1985). Mathematical relationships linking process parameters to welding emissions have been documented in literature, while epidemiological studies related to health impacts are based on statistical analysis. From Fig. 1, the process parameters (welding current, voltage, speed, shielding gas flow rate, shielding gas composition, and filler wire composition) function as independent variables, represented as green nodes.

Any change in independent variables will affect intermediate variables (blue nodes), which are the variables associated with the fume emissions. Variables representing emissions, such as fume generation rate, fume composition, particle size, and cumulative exposure time, influence worker health (red target node). Intermediate variables are dependent variables whose values need to be monitored using sensors or, need to be simulated or predicted based on models. They also function as hubs within the graph model and provide a bridge for knowledge integration from the two domains.

In addition to the intermediate variables, worker health is affected by exogenous variables (grey nodes), such as smoking habits, age, and prior health condition. The causal relationships between these variables can be established using experimental data, equations, and/or functional models. Here, causal relationships between variables have been established using the dimensional analysis conceptual modeling (DACM) framework (Coatanéa et al., 2016). The DACM framework is a systems design approach that uses functional modeling, dimensional analysis, and bond graph theory to model the cause-effect relationship between variables in a system in the form of a causal graph. DACM can also be used to build a causal graph in a reverse engineering fashion when equations are known.

A causal graph can be used as a precursor to the development of machine learning models, such as BNs, for simulation (Nagarajan et al., 2018; Mokhtarian et al., 2019). BNs use Bayesian inference for computing conditional probabilities for variables represented in the graphical model. The BN satisfies the Markov chain, meaning that the conditional probability of a node is independent of its non-descendants, which simplifies the computation of the joint probability distribution of the whole network (Pearl, 2000). Causal relationships that exist between process parameters, machine specifications, measured emissions, prescribed safety measures, practiced safety measures, and worker health could be used to generate BN models. The BN model can be updated based on new information or knowledge that is obtained as evidence. The emphasis given to cause-effect relationships via the use of a causal graph provides an intuitive approach to explicitly evaluate the uncertainties in potential outcomes with the use of probability tables (Wade, 2000; Ascough et al., 2008). Thus, the BN can serve as an interactive multi-objective decision-making approach, wherein the computational losses can be minimized by using available knowledge, combined with a statistical framework, taking into account uncertainties in variables, decisions, and outputs of different domains.

Using this approach, the BN will comprise multiple nodes that represent the different variables of the system of interest. These nodes will be connected in the form of direct acyclic graphs (DAGs), developed based on their causal relationships. The causal relationships shown in Fig. 1 will help generate the DAG for worker health for the WAAM process. Apart from the parameter and dependent nodes, the network may also contain constraint nodes. Constraint nodes are Boolean (true/false) clauses that help restrict the network from generating conditional probabilities for certain interactions between nodes that do not exist in the physical world or that are inaccurate.

Simulation of the BN model can enable the following: (1) monitoring the effect of changes in process parameters on emissions and worker health, (2) suggesting safety equipment and procedures required based on exposure time, fume composition, and fume generation rate, and, conversely, and (3) prescribing optimal process parameters based on available safety equipment to control emissions rates and prevent adverse worker health effects. The implementation of such a model would allow engineers and managers to monitor shop floor processes and ensure the safety of workers a priori or as conditions change.

## 4. Discussion and future work

Industries adopt new technologies in order to remain competitive in the marketplace. Effects of new technologies are often uncertain at the outset, and over time new information regarding their effects on workers becomes better known. Modeling new processes and systems must utilize the breadth of knowledge available at the earliest phases to develop models more quickly and efficiently. Pre-existing manufacturing knowledge is available in many different forms and spans across various science and engineering domains due to its multidisciplinary nature, especially for new manufacturing technologies (e.g., additive manufacturing processes).

Simulation of developed models must be flexible to enable use of new-found knowledge when making predictions. The graph-based modeling approach presented here enables cross-functional integration of knowledge of different forms, using causal relationships and correlations between the different variables in a system. The causal graph allows decision makers to bridge knowledge in different domains and acts as a precursor to the development of machine learning models, such as Bayesian networks (BNs), enabling rapid, system-wide simulation and scenario analysis.

Future work will develop and implement a BN model for monitoring worker health and safety in WAAM operations. Pre-existing knowledge and experimental data will be used to train and simulate the developed BN. The network will be trained and simulated using different sources of data, including pre-existing knowledge, sensor data for machine parameters and emissions, accident reports, machine-specific safety brochures, and standards from worker health and safety organizations. Finally, connecting the BN model to different sources of data that can be utilized by the network in the form of evidence during simulation will provide a basis for reinforced learning of the existing causal relationships.

## CRediT authorship contribution statement

**Hari P.N. Nagarajan:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Suraj Panicker:** Conceptualization, Methodology, Investigation, Writing - original draft. **Hossein Mokhtarian:** Methodology, Investigation, Writing - review & editing. **Eric Coatanéa:** Methodology, Investigation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Karl R. Haapala:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

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