

Impact of various STOP measures on welding fume workplace exposure: A quantitative, predictive approach

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Abstract

The proposed sixth amendment to Directive 2004/37/EC on carcinogens, mutagens and reprotoxic substances (CMRD) of the European Parliament and of the Council, which includes welding fumes containing nickel (Ni) and hexavalent chromium (Cr(VI)) in Annex I, is expected to significantly increase attention to occupational exposure in welding environments. In this context, the implementation of the STOP principle, as required by the CMRD, becomes a central element for exposure control in welding shops. Although the technical measures to reduce the air pollution - such as process and electrode selection, low-fume consumables, local fume extraction and optimized ventilation - are well known and established, their quantitative impact on occupational exposure remains insufficiently characterized.

To address this gap, the Austrian Welding Society (ÖGS) developed the cloud-based web application “ÖGS WeldAir”, enabling the combined evaluation of exposure reduction measures. The tool provides high temporal resolution predictions of welding fume-, Ni-, Cr(VI)- and Mn- indoor concentrations under varying conditions, including different arc welding processes, consumables, duty cycles, various extraction systems and ventilation times, and benchmarks them against national exposure limits.

Validation results demonstrate the model’s potential as a predictive tool for risk-based assessment for welding workplaces.

1. Introduction

The hazard potential of chemical and naturally occurring substances to human health is today well characterized and can be assessed with increasing statistical robustness based on continuously expanding epidemiological and toxicological data sets. These scientific insights are the basis for national legislation [1]-[3], in which maximum permissible limits for occupational and environmental exposure to critical substances are defined to ensure an adequate level of protection against adverse health effects.

However, deriving limit values for carcinogenic substances is inherently complex, as it depends on long-term epidemiological evidence and is generally linked to probabilistic risk estimates rather than clearly defined thresholds. Consequently, risk assessment for these substances typically follows a minimization approach instead of defining a “safe” exposure level.

In 1989 the European Commission enacted Council Directive 89/391/EEC [4] to establish a general framework for improving occupational safety and health by defining uniform European minimum standards, introducing preventive principles, employer responsibilities, and worker participation across all sectors. Within this framework the EU-Directive 2004/37/EC on carcinogens, mutagens and reprotoxic substances (CMRD) [5] was established in 2004 with the aim to protect workers from a critical exposure to carcinogenic, mutagenic, and reprotoxic substances in industrial environments.

In addition to complying with minimum occupational exposure limit values for selected substances employers are also required to apply a strict hierarchy of control measures. The CMRD notably mandates the STOP principle (Substitution, Technical, Organizational and Personal protective measures), whenever exposure to listed carcinogens cannot be avoided. Furthermore, the CMRD is continuously updated in line with scientific progress, so it remains highly relevant for exposure control strategies.

As welding fumes are complex aerosols containing hazardous metallic components and their oxides which are associated with adverse health effects [6], the control of occupational exposure to welding fumes has gained increasing importance in recent years, also driven by advancing scientific evidence and evolving regulatory frameworks. New epidemiological findings summarized in the IARC Monographs (Vol. 118, 2017/2018) [7] have demonstrated that welding fumes significantly increase the risk of lung cancer but also of kidney cancer among welders. In addition, ultraviolet (UV) radiation generated during arc welding is in association with skin cancer and ocular tumors. Finally, this IARC study classifies welding fumes and UV radiation as carcinogenic, irrespective of materials and welding processes applied.

Based on the IARC study, the actual proposed sixth amendment to Directive 2004/37/EC (CMRD) [8] explicitly includes now welding fumes containing nickel (Ni) and hexavalent chromium (Cr(VI)) in CMRD Annex I (list of substances, mixtures and processes). While this regulatory update does not introduce new exposure limit values - given that occupational exposure limits (OELs) for Ni and Cr(VI) were already significantly reduced within the European Union in early 2025 - it is expected to substantially increase the awareness of carcinogenic risks associated with welding. In contrast, the inclusion of cobalt (Co) – along with

corresponding threshold levels – in the CMRD list of carcinogens is new. Once implemented, this amendment will intensify both regulatory and practical discussions regarding effective exposure reduction strategies and risk assessment, particularly in small and medium-sized welding enterprises. In this context, the systematic evaluation and prioritization of measures within the STOP hierarchy becomes increasingly relevant.

Exposure to welding fumes can be reduced by a wide range of organizational and technical measures, including the selection or modification of welding processes, the use of low-fume consumables, local fume extraction systems and general hall ventilation installations [9]. However, despite their widespread application, the quantitative effectiveness of these measures under realistic workplace conditions remains insufficiently characterized. Furthermore, the currently promoted assessment of the welding processes [10], [11] is inherently inadequate, as it relies primarily on fume emission rates that do not account for process-dependent differences in Ni-, Cr(VI)-, Mn- fume concentrations and the published ranges of the fume emission rates, especially in case of cored wires, do not consider the state of the art for these processes.

In practice, the evaluation of exposure reduction strategies relies predominantly on a realized shopfloor installation followed by welding tests and occupational exposure measurements. This approach is expensive, resource-intensive, burdens welder and limits the systematic assessment of combined or parameter-dependent effects. To overcome such a “trial and error” procedure, more precise predictive approaches are needed to enable efficient, flexible and quantitative assessment of welding-related exposure scenarios without exposing welders to unnecessary risk.

2. Workplace exposure measurement

As occupational exposure limits are established in national legislation, exposure measurements must follow clearly defined procedures and methodological requirements [12]-[14]. However, stakeholder discussions during this work on exposure scenario prediction indicated that exposure measurement methods and statements from welding consumable fume emission data sheets require a brief clarification.

2.1. Personal welding fume exposure versus consumable fume emission

In the field of occupational safety and health, the amount of hazardous substances that welders inhale is the key issue. Therefore, their concentration, defined as mass per volume air, near the welder's breathing zone is measured and compared with relevant national concentration limit values. This is the standard approach required by labor inspection authorities.

On the other hand, consumables are often characterized by the quantity of fumes they produce during welding. In this case the electrodes are welded in a standardized chamber and the rate of emitted fume, defined as mass per welding time, is determined. That's why personal exposure concentration and fume emission rates are not comparable, but somehow dependent. But this will be discussed later in this paper.

2.2. Gravimetric versus optical dust and fume exposure measurements

Exposure to particulate hazardous substances, including wood dust, quartz dust and welding fumes, is typically assessed gravimetrically by collecting particles on filters under defined sampling conditions. Whereas the sample mass required for fume emission analysis directly from consumables can usually be collected within minutes, workplace exposure measurements generally require several hours of sampling to obtain sufficient material. As the subsequent chemical analysis is performed in certified laboratories, this approach is relatively costly and time-consuming, and final results may not be available up to several weeks. Nevertheless, gravimetric analysis remains the reference method for occupational exposure assessment, as its results can be directly compared with applicable legal exposure limits.

In contrast, compact digital sensors for measuring airborne particles, particularly so-called low-cost sensors, have developed rapidly in recent years. These devices typically consist of a light source, a detection chamber and a photodetector, and determine particulate matter (PM) optically. Particle-laden air is drawn into the sensor and guided through a light beam, usually generated by a laser. Interactions between particles and light cause scattering and, in some cases, absorption. A detector measures the intensity of scattered or transmitted light at one or more predefined angles, which are specified by the sensor manufacturer. The resulting optical signal is then converted into an airborne particle concentration. However, as this measurement principle does not

provide information on particle composition, calibration with the same type of dust is required to convert measured particle concentrations into exposure values that can be compared with applicable exposure limits.

Owing to their optical measurement principle, these sensors generally cannot detect particles below approximately 300 nm. Particles larger than about 12 µm are also difficult to sample efficiently without an additional pump. Consequently, they are mainly suitable for assessing the respirable and thoracic particle fractions, whereas ultrafine particles (UFPs) and the inhalable dust fraction up to 100 µm are not fully captured.

Despite these limitations, sensor-based systems provide high temporal resolution, typically in the order of seconds, enabling concentration changes to be visualized almost in real time (Fig. 1). Since PM exposure assessment is primarily based on mass concentration, the limited detection of UFPs is generally of minor relevance in this context. In addition, these systems are comparatively inexpensive.

Compared with gravimetric methods, sensor-based measurements offer several practical advantages. Their lower cost enables denser monitoring across larger worker populations, while the use of multiple sensors supports spatially resolved assessment of particulate matter. Their high temporal resolution allows short-term exposure peaks to be linked to specific activities or process conditions, and the immediate availability of data supports the rapid identification of critical exposure situations and timely preventive action. Although measurement repeatability is generally good, the accuracy of the displayed exposure values depends strongly on calibration and the selected reference dust. For this reason, optical sensors are currently not accepted as a reference method for occupational exposure measurement, but they are a very helpful monitoring tool.

2.3. Chemical analysis of fumes – possible Ni, Cr artefacts

Various fume data sheets for different consumables were used as a basis for this work. Notably, small amounts of Ni and Cr were reported in the data sheet even for electrodes containing neither chromium nor nickel in the coating or core wire. The origin of these findings has not yet been investigated in detail; however, clarification is required because even trace amounts of carcinogenic elements are relevant for exposure assessment. If the consumable itself is not the source, possible explanations include elemental carryover from the fume box or artefacts introduced during chemical analysis. The collected fume material is often analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES), which detects element-specific radiation at characteristic wavelengths. However, emission lines of different elements may overlap or occur very close to each other, potentially leading to misinterpretation of analytical results. This is particularly critical in transition-metal systems such as Fe-Cr-Ni-Co-Mn-Cu, which include several elements of toxicological and carcinogenic relevance. Therefore, further method-focused analytical investigations are needed to reliably define fumes as Ni-, Cr- or Co-free.

3. The STOP principle applied to welding

In case of welding there are many options to follow on the STOP principle: From changing the welding process or electrode type, to using low-fume electrodes and further on from installing and positioning of local exhaust ventilation (LEV) to utilizing shop ventilation systems [9]. Additionally, the coordination of welding stations in respect to welding time and parameters could help to keep the workplace exposure below the legal national limits.

3.1. Substitution

To reduce occupational risk for welders, fumes should be captured as close as possible to the emission source [15]. One effective strategy is to shift to welding processes with lower fume emissions [16], although this may be limited by economic, technical or welder-related constraints. As noted above, process selection should not rely solely on general fume emission rates reported in the literature; instead, consumable-specific emission rates and the chemical composition of the generated fumes should also be considered. In particular, low-fume and/or Ni-, Cr(VI)- and Mn-reduced electrodes [17], [18], optimized welding processes [19], CO₂- or O₂-reduced shielding gases [20]-[22] and smaller-diameter electrodes [23] can substantially reduce exposure.

3.2. Technical measures

LEV is another key measure for exposure control. Systems positioned close to the arc, such as on-torch extraction and extraction nozzles, are generally the most effective and should be preferred because they can reduce the welder's direct contact with the fume column best. It has to be considered that their capture efficiency depends mainly on the extraction volume, the distance from the emission source and the geometry of the torch [24] or nozzle.

Mobile extraction arms can also be effective when positioned within the fume column – but it is already visible and often shown in practical demonstrations, that their capture efficiency sharply decreases, when their hoods are just partially positioned to the fume column.

Larger ceiling-mounted extraction hoods are designed to capture a substantial fraction of the fumes generated above the welding station. However, they do not prevent the welder's head from entering the fume column and may therefore lead to elevated personal exposure. The same limitation applies when mobile extraction arms are positioned too far above the arc. In this case the standing and sitting position of the welder already can have an influence on his personal exposure [25].

Finally, hall ventilation systems lower overall workplace exposure by increasing the air exchange rate. Depending on their design, they provide either stratified ventilation, which supplies cleaner air to the welder's breathing zone, or mixed ventilation.

These measures are well established [9], [26]-[29]; however, their quantitative impact on workplace exposure has so far been difficult to assess. While modelling of hall ventilation concepts is supported by pragmatic approaches and experience of ventilation equipment suppliers, the quantitative description of LEV efficiency remains challenging. A key limitation is the strong influence of extraction-device positioning relative to the welding fume column, which is difficult to describe in a generally applicable model.

3.3. Organizational measures

There are also some organizational measures, for instance welding in enclosed, separated areas will reduce the risk to uninvolved workers. Limiting the time welders spend in exposed areas and coordinating welding times in a targeted manner can further lower occupational exposure.

3.4. Personal protective measures

Powered air-purifying respirator (PAPR) systems are highly effective in protecting welders. By supplying filtered air to the welding helmet from behind the welder, they substantially reduce personal exposure during welding [30]. However, welders often open the PAPR helmet immediately after welding. As a result, protection is mainly limited to active welding time, while exposure may continue during remaining working periods if the surrounding air is contaminated. Therefore, PAPR systems should not be considered a stand-alone measure for controlling occupational exposure. In addition, strict cleaning schedules are required to maintain respiratory hygiene.

4. Simulation of workplace exposure to welding fumes

As described, the mandatory STOP principle offers several measures to reduce occupational exposure in welding. However, their individual and combined effects on workplace exposure have not been quantitatively assessed. The main reason therefore is the extremely difficult description of the welding fume flow. This gas flow in indoor environments is governed by interacting factors such as thermal convection, turbulence, room geometry, internal installations, heat sources, fans from electrical equipment, air supply and exhaust conditions, particle transport and diffusion, as well as transient flow effects caused by opening doors or windows, but also by worker or vehicle movement.

Computational fluid dynamics (CFD) can be used for simulation; however, the complexity of an indoor gas flow leads to nonlinear partial differential equations that require substantial simplifications and carefully defined boundary conditions. Although CFD simulations of welding fumes have been reported [31], [32], they remain limited in scope, focusing mainly on specific aspects such as particle distribution or flow conditions in nozzles, and are therefore not suitable for describing the effects of exhaust devices.

To address this gap, the Austrian Welding Society (ÖGS) established the ERFA ÖGS H&S - an expert group representing consumable development, welding equipment design, ventilation technology, welding shops and accident prevention institutions. In several workshops a common simplified model-based design approach of industrial building ventilation systems was analyzed and applied for welding fume concentration calculation. Based on the findings a project was initiated, to develop a digital tool, based on simplified models, to quantify the impact of STOP - measures on workplace exposure and to predict airborne concentrations of welding fumes, Ni, Cr(VI) and Mn based on emissions from different consumable types. One of the big challenges thereby was the modeling of the effects of LEV's.

4.1. Modeling fume emission source

Most particulate emissions in welding fumes originate from the consumable rather than the base material. Approximately 95% of fume particles are attributed to the filler material, while only about 5% derive from the base metal [33]. As a result, the chemical composition of welding fumes is mainly determined by the filler material. Because consumables are usually compositionally similar to the base metal, the electrode's fume data sheets are used as the base for describing the fume source. The consumable-specific fume data sheets, which are established according to standards at 90% of the electrode's maximum amperage [34], provide a robust basis for quantifying emissions. When high alloyed fillers are used, they generally represent the more critical emission source due to their carcinogenic constituents; therefore, using these "high amperage" data sheets may lead to a slightly conservative overestimation of exposure. The different types of electrodes and their fume data sheets represent thereby also different welding processes.

Because fume data sheets report the fume emission rate (FER) and fume composition for 100% arc-on time, exposure prediction must account for the actual arc-on time. The model therefore incorporates the welding duty cycle, as known from the welding equipment, defined as the percentage ratio of welding time to total time within a 10-minute reference interval.

4.2. Modeling hall ventilation effects

Calculation models based on air exchange rates are well established, proven in practice and therefore also applied in this model. It has to be distinguished between an (ideal) mixed and a stratified ventilation, which takes the beneficial effects of a floor-level air supply into account. For the model an ideal mixed ventilation was assumed. If the ventilation system is turned off, natural ventilation is assumed in the model.

However, conventional approaches typically use average fume emission rates (FERs) for different welding processes from the literature and do neither account for actual arc-on time nor fume composition.

4.3. Modeling LEV efficiency

As noted above, the position of the LEV relative to the fume column is critical for its extraction efficiency; however, no comprehensive model has yet been available to describe this effect. The main challenge is to represent the thermally driven welding fume column in a simplified but meaningful way. Two established approaches for describing the fume column and the efficiency of local exhaust systems are available [35], [36] and were therefore used as the basis for the present model.

For this model, a simplified cone approach was selected [35] (Fig. 2). Although this approach does not explicitly account for fume turbulence or lateral air flows, it defines a practical geometric relationship between the LEV and the fume column. The thermal air flow rate within the fume cone is calculated from the electrical power consumption of the welding process [36].

As an additional simplification, the suction area in front of an extraction tube is assumed to be circular and limited by the tube diameter [36].

It was further assumed that the LEVs are designed in a proper way by the manufacturer: the air flow rates of the LEVs correspond to their geometric design and the fluid dynamics requirements within the LEV are met.

4.4. Validation of the model

The emission, hall ventilation and LEV efficiency models were combined and validated. For existing hall ventilation systems in halls with volumes of 10.000–15.000 m³ without LEV the calculated concentrations showed a close agreement with measured

workplace exposure values.

To validate the fume column and LEV efficiency models, a dedicated test setup was used in a small welding laboratory designed to minimize transient air flows and to promote rapid air mixing. Because of the limited room volume of 150 m³, the mobile LEV system, with an exhaust flow rate of 1000 m³/h, already acted as general room ventilation when operated continuously. Therefore, the LEV was operated only during arc-on time.

SMAW with an unalloyed Ø 6 mm electrode was selected to generate high fume emissions and thereby make the influence of hood positioning more evident; however, the model is not limited to SMAW. The exhaust efficiency was calculated as a function of hood position relative to the arc and the fume cone (Fig. 3) and subsequently validated by welding trials, showing good agreement with the experimental results [37].

Because the model provides high temporal resolution predictions of fume, Ni, Cr(VI) and Mn workplace exposure, it was validated against real time data generated by optical sensors calibrated for welding fumes.

A comparison between optical sensor data and gravimetrically measured exposure values was outside the scope of this project.

The model enables a quantification of the effect of hood center position relative to the welding arc (Fig. 4). Even a small horizontal displacement of approximately 15 cm from the arc centerline reduces exhaust efficiency, while at 30 cm the efficiency falls below 20%. Similarly, efficiency decreases when the hood is positioned more than 1 m directly above the arc. These findings apply under idealized conditions without cross air flows and may considerably change under real conditions, especially if the hood is placed in the unstable area of the fume column.

The model points out a high efficiency of the hood up to 1m directly above the arc under “ideal”, cross-flow free conditions. Nevertheless there is a clear recommendation for a correct positioning of the hood: Taking into account real welding workplace conditions with cross air flows and keeping in mind that the exhaust hood of the LEV should also physically prevent the welder from accidentally exposing his head to the fumes the hood should be placed 0.3-0.4m at an inclined angle (30–45°) directly above the arc. Meanwhile exhaust nozzles extraction high should not exceed 0.15m [38].

5. Digitalization of the developed model

Based on the positive evaluation of the model, the cloud-based web application “ÖGS WeldAir” was developed [39]. It improves usability, provides free 24/7 access, and supports a better understanding of STOP measures by digitally quantifying their effects on workplace exposure without the need for welding trials, direct fume exposure of welders or exposure measurements. The application also enables systematic evaluation and comparison of different control measures. The design as a web app offers additionally the possibility to use the individual browser-integrated translation function which allows the app to be used in various common languages on laptops, tablets and smartphones. As the target of the web app is a prediction of workplace exposure, the adjustable time interval is set to 1 hour, as smaller time units are seldom used in production planning.

Figure 5 shows an example of an ÖGS WeldAir prediction for a defined SMAW welding shop over a full working shift with two breaks. The scenario includes hall ventilation operated at a reduced level and an LEV system with moderate efficiency, reflecting inadequate hood tracking. The predicted PM fume and Mn concentrations are displayed together with the corresponding national limits. The simulation shows that, although the total fume concentration remains well below the limit, the permissible Mn limit is almost reached; corrective measures can therefore be evaluated systematically.

In contrast, optical sensors require actual fume generation to produce a comparable concentration profile and would indicate a clearly acceptable PM level, while the nearly critical Mn concentration would remain undetected and do not give cause to reconsider the exhaust concept. Similarly, gravimetric measurements require also real fume generation but provide only shift-average values for fume and Mn, available typically after several days, which limits their usefulness for timely optimization of exhaust systems.

6. Risk assessment of STOP-measures on workplace exposure

To figure out the possibilities of the workplace exposure simulation a short example is shown in which all previously discussed STOP measures are assessed and their impact on workplace exposure caused by various welding cycles are demonstrated. The effects of different STOP measures were predicted using the “ÖGS WeldAir” web app for a standard hall measuring 30m × 10m × 6m with one 316L/304-welding station. The scenario assumed a full welding shift; starting at 7:00, with 1-hour breaks at 10:00 and 13:00, and a welding duty cycle of 20%.

For a greater visibility in this paper, the concentration profiles for total fume, manganese, Cr(VI) and Ni were color-code framed according to national workplace exposure limits – in this case for Austria: red for exceedance, orange for values at the limit, and green for values below the limit. The first diagram shows the evolution of the fume-, the second the Mn-, the third the Cr(VI)- and the fourth the Ni- concentration during the shift.

It is necessary to state that the predictions are done for the workplace concentration and do not take into account if the welder is full-time or only part-time at his workplace. Also, the physical position of the welder in respect to the fume column is not considered which could have a significant influence on his personal exposure. That’s why the predictions may not directly correspond to the real welder exposure levels, which are finally relevant for labor inspection authorities.

6.1. Substitution of process

For the assessment of the welding process the simulation was done without any further extraction/ventilation measures, only natural ventilation was considered, for welding of 316L base material (Fig. 6). SMAW, FCAW, GMAW, MCAW are characterized by a typical consumable, the calculation was done based on the relevant fume datasheet. In all considered cases the fume is clearly beyond the national limit, but at least one component of the fume exceeds the national limit. Only metal cored wire welding could provide an overall, but borderline acceptable result. But it is evident, that additional exhaust measures must be taken into account, to meet the national requirements in any case.

Based on this calculation, the differences in the results are not that big as expected from the purely FER -based assessment using published average process-related FER`s.

6.2. Substitution of electrodes

The assessment in case of consumables is demonstrated for stick-electrode welding of 304 base material (Fig. 7). The electrode diameter but also the alloy type was changed and their influence on the exposure evaluated. The beneficial effect of thinner electrodes becomes visible.

6.3. Technical Measures

The assessment of technical measures is done for FCAW /Flux cored wire (316L; Ø1,2mm; Ar + 18% CO₂).

6.3.1. Hall ventilation

The influence of a hall ventilation for the considered scenario (hall size 1800m³, 316L base material, FCW) with different air exchange rates (AER) compared to the natural ventilation is shown in Fig. 8. Already a small-sized ventilation is in this case efficient.

6.3.2. Lokal exhaust ventilation (LEV)

The effects of a mobile extraction system (suction effect: ~80%) and an on-torch exhaust system (suction effect: ~75%) are shown in Fig. 9. It has to be mentioned that the positioning of the LEV plays a major role on efficiency. Therefore, realistic values are chosen for the calculation.

6.4. Organizational Measures

Organizational measures can also reduce exposure. In addition to shorter welding times, as shown in Fig. 10, time-restricted access to the welding area can further reduce welders' exposure.

6.5. Personal Measures

Because ÖGS WeldAir was developed to assess workplace exposure rather than exposure in the welder's breathing zone, the latter cannot be explicitly represented. If his breathing zone remains outside the fume column and he is all the time at this workplace, the predicted values should be comparable to his "personal" exposure. Under practical conditions, however, accidental exposure to the emitted fume during welding is likely. PAPR systems are therefore strongly recommended for welding operations. However, they provide protection only during arc-on time and only while the helmet remains closed.

7. Discussion

Although occupational exposure is a key issue for most companies, the understanding and assessment of exhaust measures remain limited because of their technical complexity and a frequent lack of internal expertise. As a result, companies often implement corrective actions only after violations are identified by labor inspectorates. With welding fumes containing Ni and Cr(VI) expected to be explicitly classified as carcinogenic under EU regulation, they will receive greater attention in workplace risk assessment. Consequently, systematic assessment of STOP measures will become increasingly important, and welding companies will require practical support in identifying effective and economically viable exposure control strategies. A quantitative evaluation of all relevant measures is therefore essential.

Because a comprehensive CFD-based simulation of workplace gas flows is highly complex and not practically feasible for routine exposure assessment, the presented approach relies on simplified models for ventilation, thermal fume column formation and local exhaust effects. The resulting predictions should therefore be interpreted as estimates rather than exact forecasts and are not intended to replace workplace exposure measurements. Nevertheless, this work provides the first digital framework for a comprehensive but simplified description of fume evolution from the arc welding process to workplace exposure, incorporating the most commonly used exhaust concepts and enabling a quantitative assessment of different measures for reducing occupational exposure to welding fumes.

There is a clear scientific interest in comparing the simulation results with real workplace measurements. However, the high temporal resolution of the model can currently be validated only using optical sensors, whereas the predicted fume chemistry requires gravimetric sampling followed by chemical analysis. At the same time, the alignment between optical sensor data and gravimetric reference measurements remains the subject of ongoing international debate. Although the present validation showed good agreement with data of a special calibrated optical sensor, a final assessment of model accuracy should be deferred until certified optical sensors for welding fume monitoring become available. Otherwise, uncertainties associated with sensor-based measurements may mask the inherent limitations of the simplified modelling approach.

As noted above, the purpose of the simulation is not to replace certified workplace exposure assessment, which for welding fumes currently relies on gravimetric sampling and subsequent chemical analysis. Rather, it is intended to support the prior optimization of exhaust measures, which must subsequently be verified by certified methods after physical installation.

8. Conclusions

In summary, the presented approach provides a practical digital framework for estimating the influence of STOP measures on welding fume exposure. Although based on simplified models and not intended to replace certified workplace measurements, it supports the prior optimization of ventilation and local exhaust concepts. Validation with calibrated optical sensors indicates plausible model behavior, while final accuracy assessment requires certified real-time monitoring methods. The ÖGS WeldAir therefore offers practical guidance for identifying effective viable exposure reduction strategies which can be economically evaluated before a physical implementation.

The main conclusions are as follows:

- ÖGS WeldAir predicts the time-resolved effects of STOP measures on welding fume, Ni, Cr(VI) and Mn exposure and relates them to applicable exposure limits.
- As the model relies on simplified assumptions, the predicted values should be interpreted as indicative estimates. Nevertheless, emissions can be described reliably using consumable-specific fume data sheets and defined welding times, and concentrations in clearly defined rooms with specified air exchange rates can be calculated with sufficient accuracy. The main uncertainty concerns local extraction systems, as their performance strongly depends on fume column modeling; therefore, established models were applied and confirmed by targeted measurements.
- The commonly used FER-based approach for ventilation design is misleading, because sharply reduced limits for critical substances such as Ni, Cr(VI) and Mn require a substance-specific assessment rather than a focus on total fume alone.
- Differences in risk assessment between welding processes such as SMAW, FCAW, MCAW and GMAW are smaller than expected when critical substances are considered.
- Risk assessment must consider all relevant critical substances; the most suitable consumable is the one with the best overall exposure balance, not necessarily the best performer for a single component.
- Hall ventilation and the local exhaust ventilation, especially the flow rate and the position of the extraction device in respect to the arc have the most dominant influence on occupational exposure.

Declarations

Data Availability

For the risk assessment the database of the free-accessible web-app “ÖGS weldAir” [39] was used.

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Authors Contributions

Conceptualization: Posch G, Reuter G; methodology: Posch G; investigation and evaluation: Posch G, Bruderhofer A; writing – original draft preparation: Posch G; review and editing: all authors; funding acquisition: Reuter G

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Competing Interests

The authors declare no competing interests.

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Figures

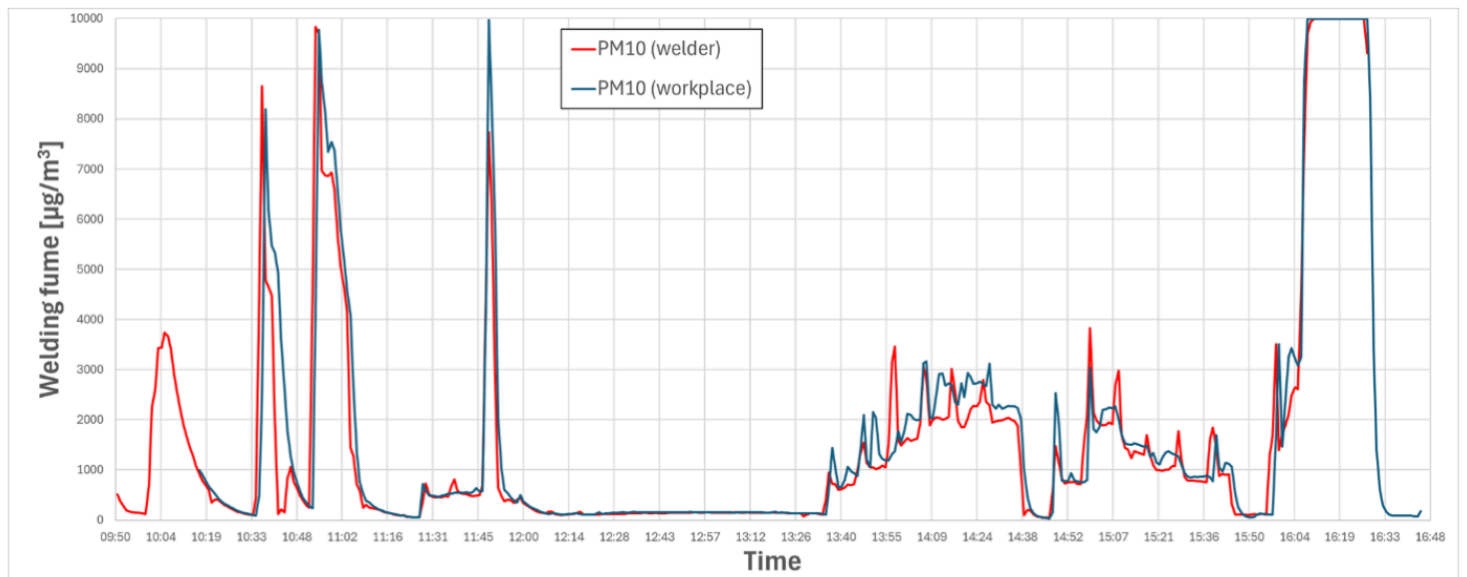


Figure 1

Temporal profile of PM10 welding fume exposure during a welder's shift if measured using optical sensors or calibrated flow welder in the fumes, not positioned directly on the welder's chest and the other 2 meters away

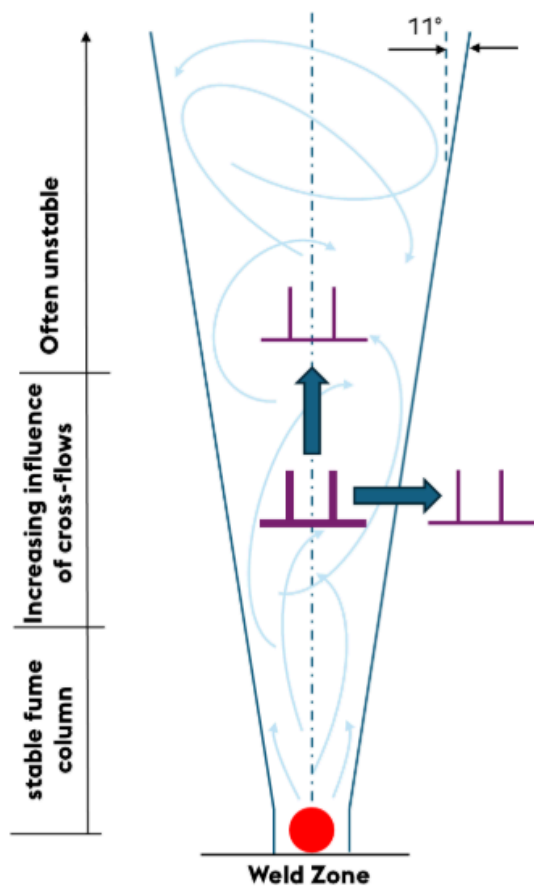


Figure 2

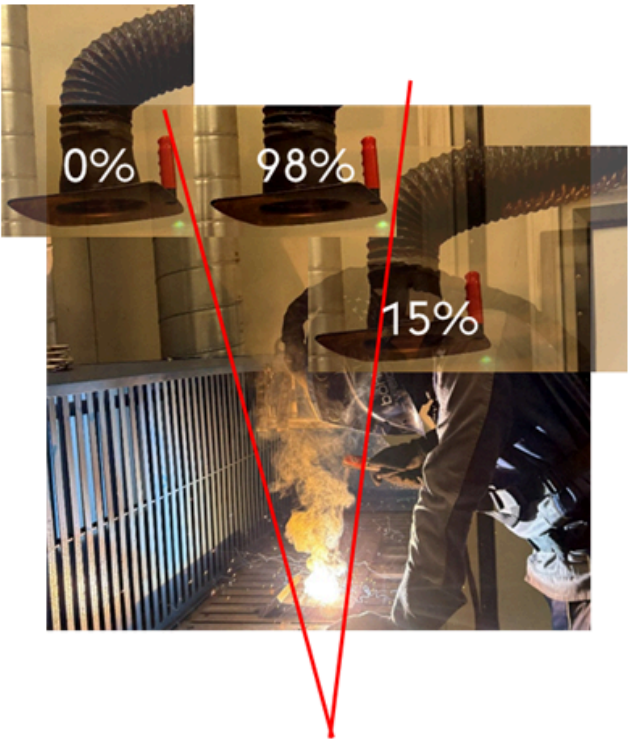


Figure 3

Predicted efficiency of LEV depending on hood positioning

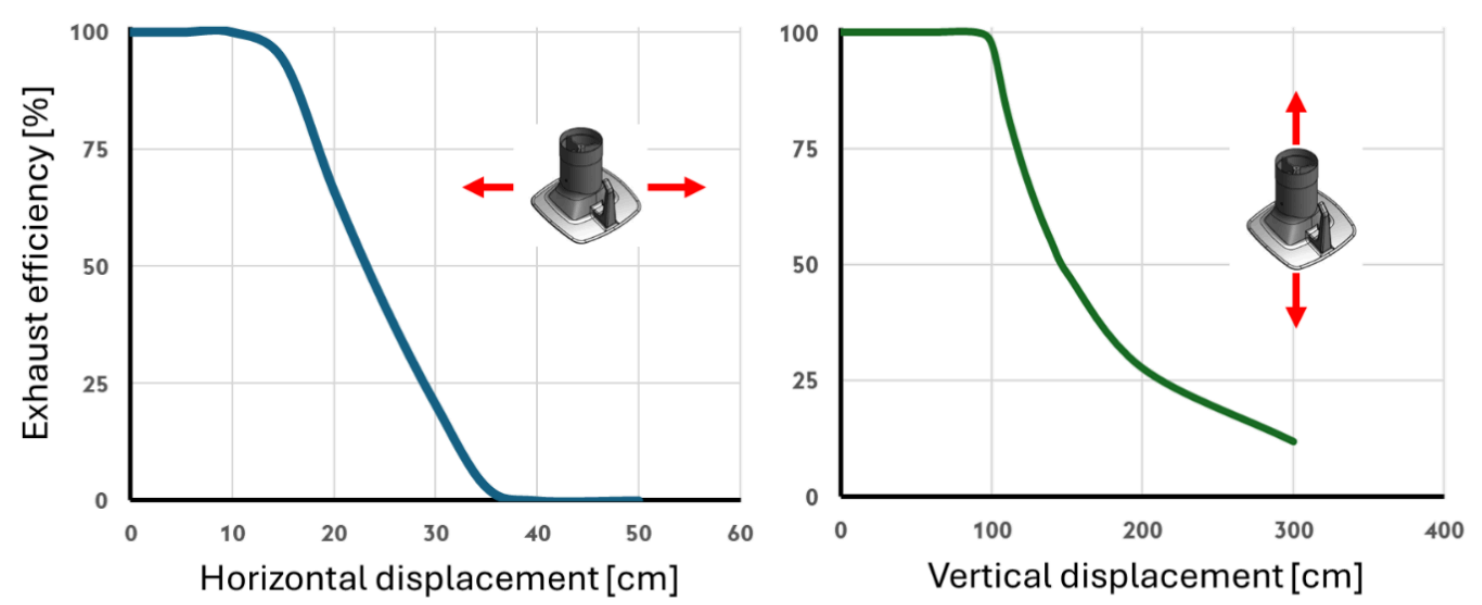


Figure 4

Effect of LEV hood center position relative to the arc on exhaust efficiency

Result (limit values AT)

Room 1

Volume: 1800 m³ | Area: 300 m² | Air exchange: 2 /h | Stratification factor: 1 | Total Suction Effect: 0.581313

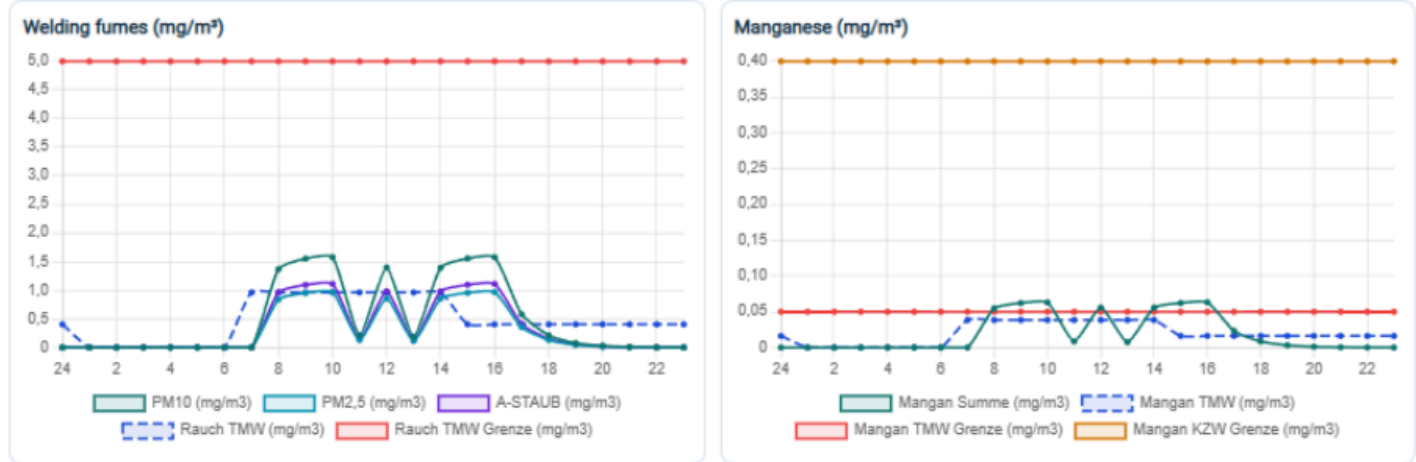


Figure 5

ÖGS WeldAir: Example for a room-specific prediction of fume and Mn workplace exposure during a welding shift; SMAW / E7018, Ø6mm. Red line: national limits (AT), orange line: short term national limits (AT), blue dashed line: shift average

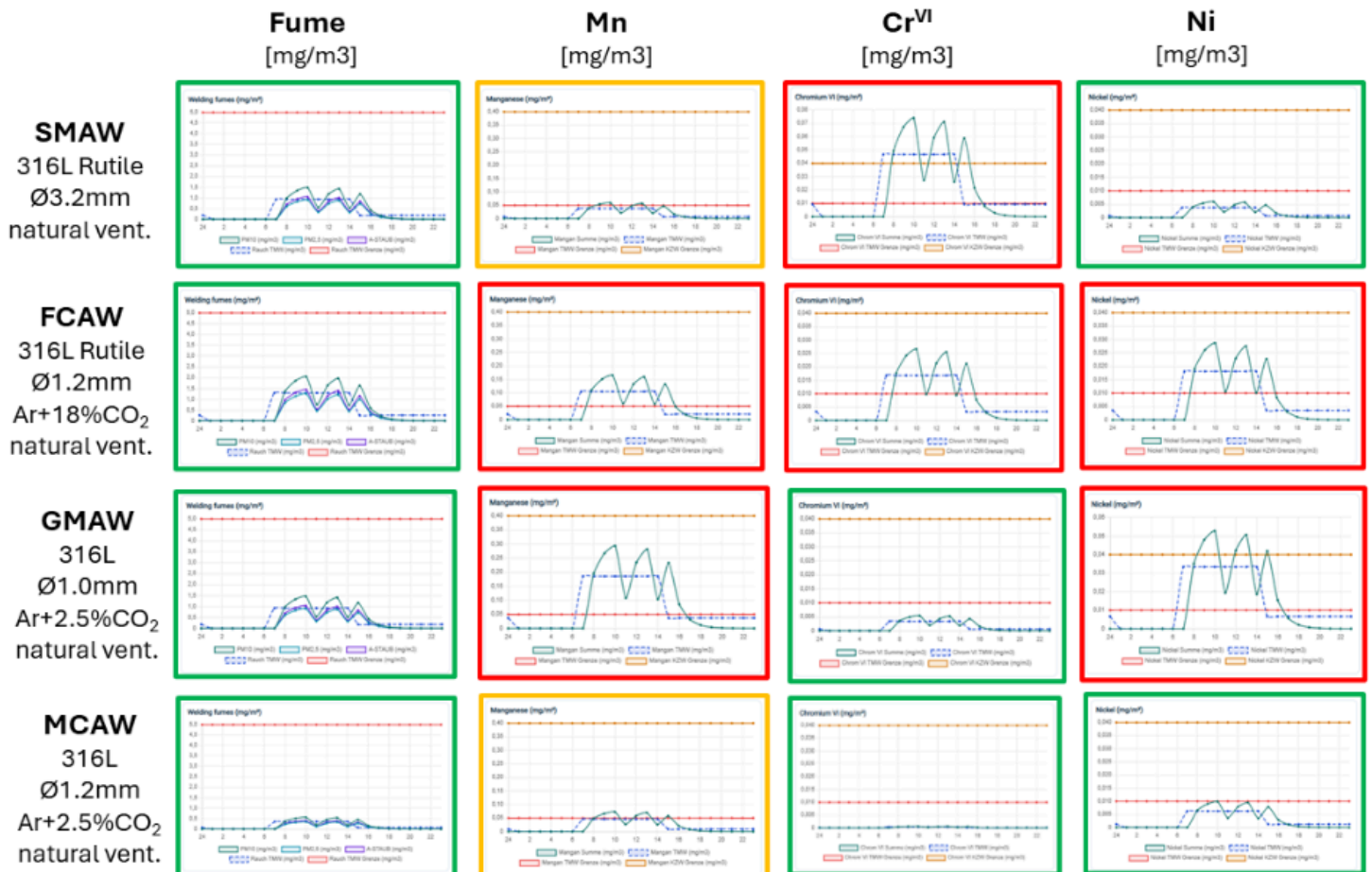


Figure 6

Assessment of the welding process; type: 316L

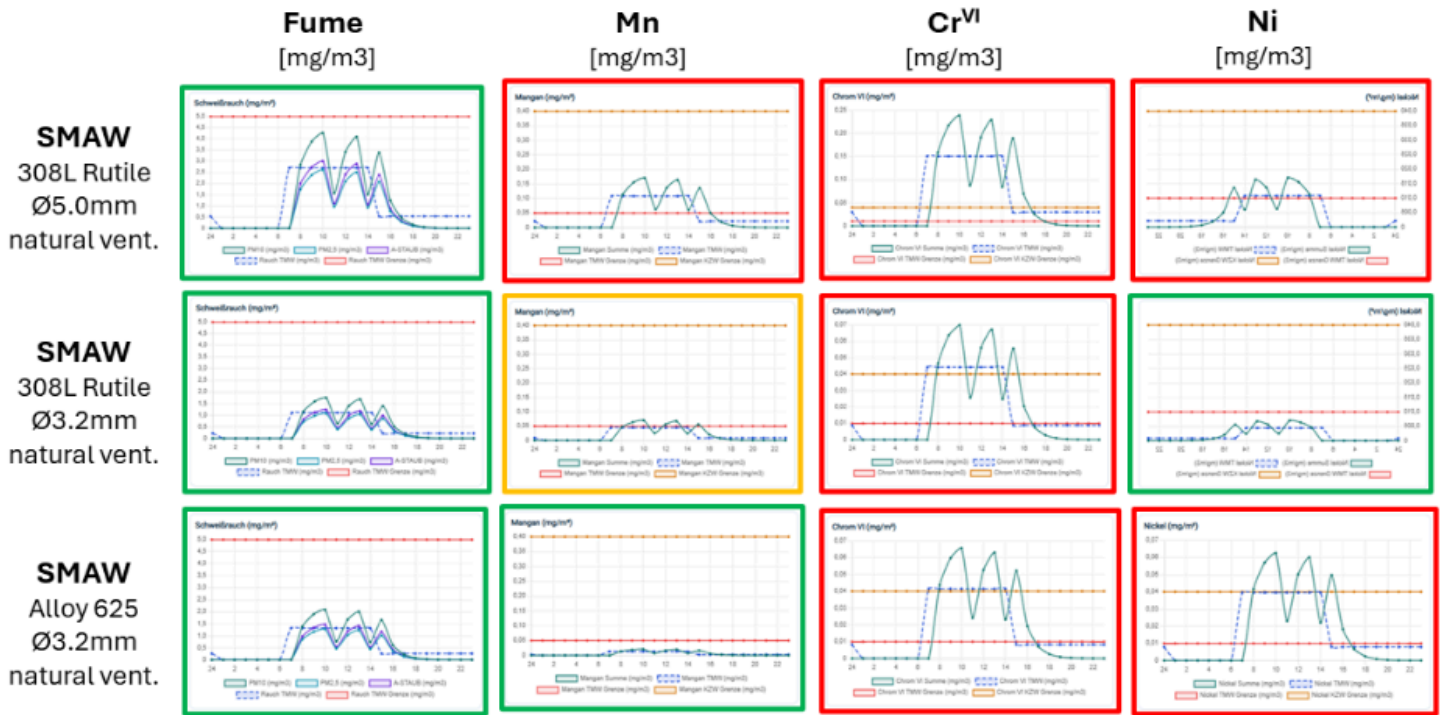


Figure 7

Assessment of SMAW-electrodes

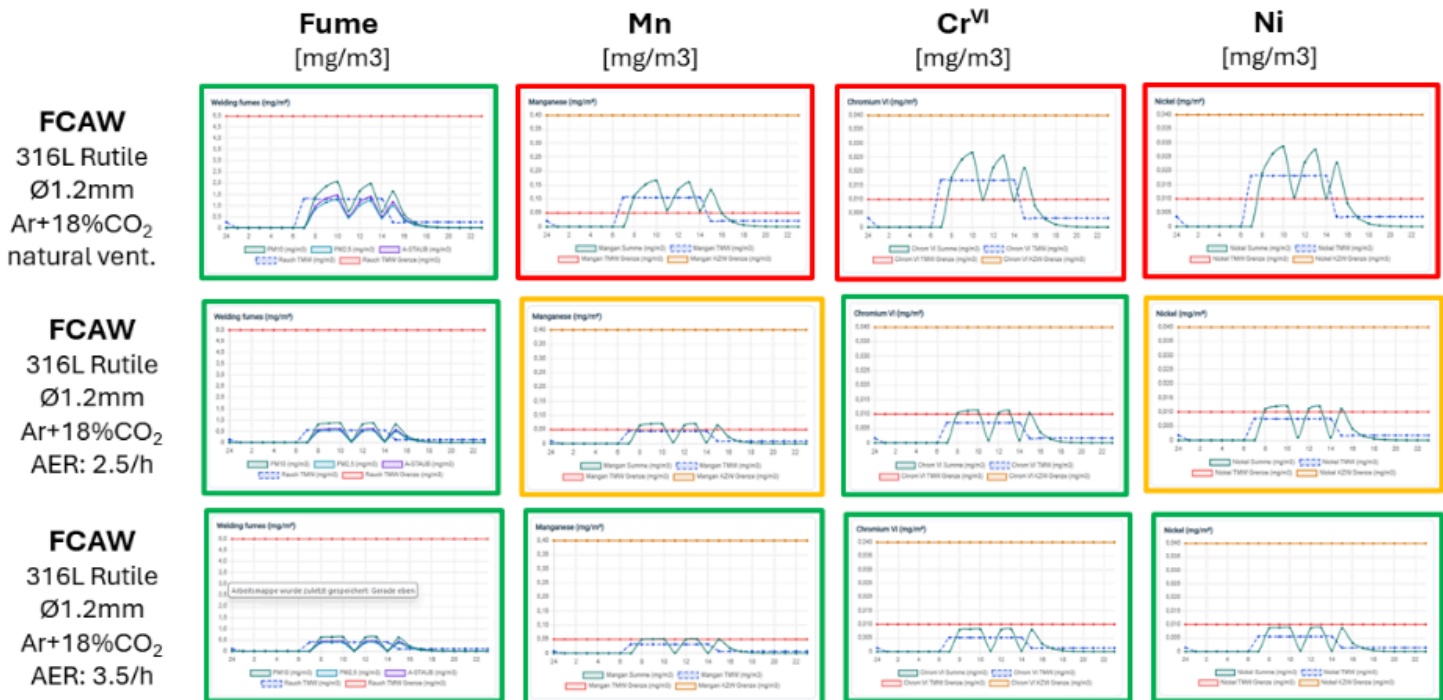


Figure 8

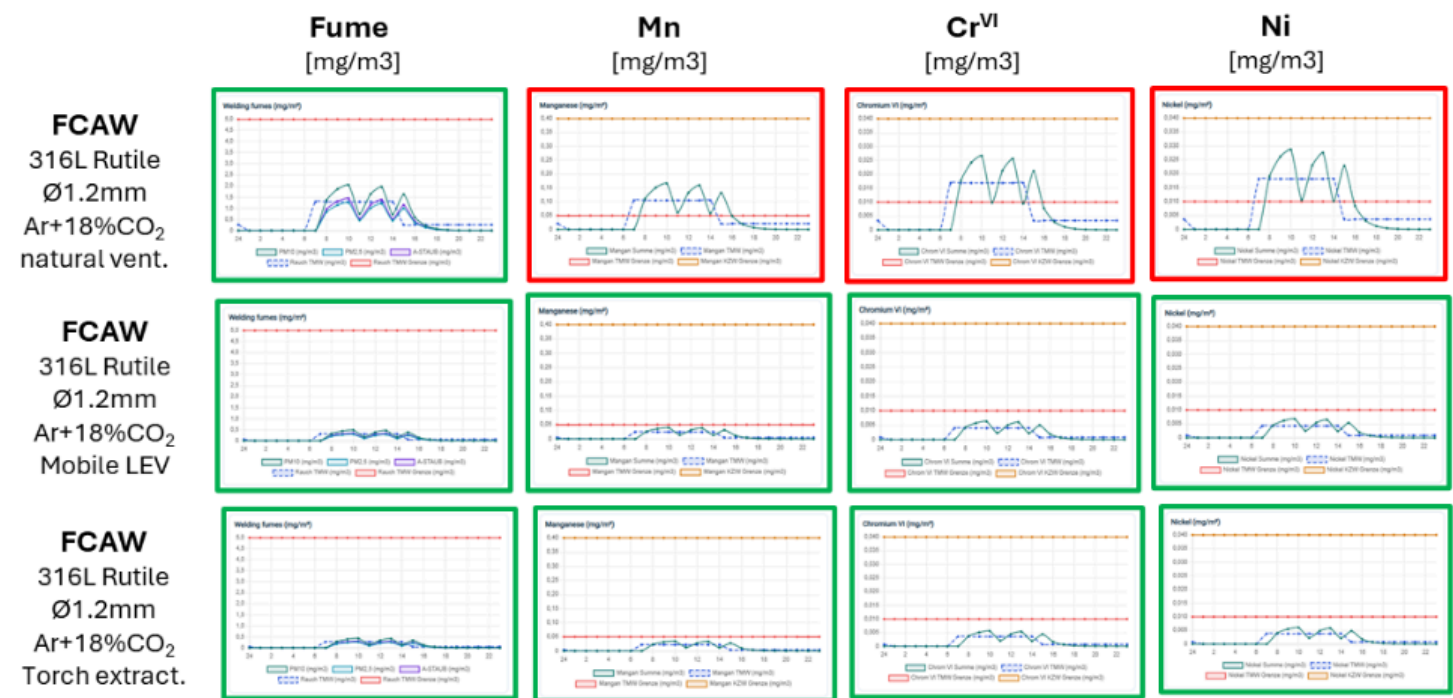


Figure 9

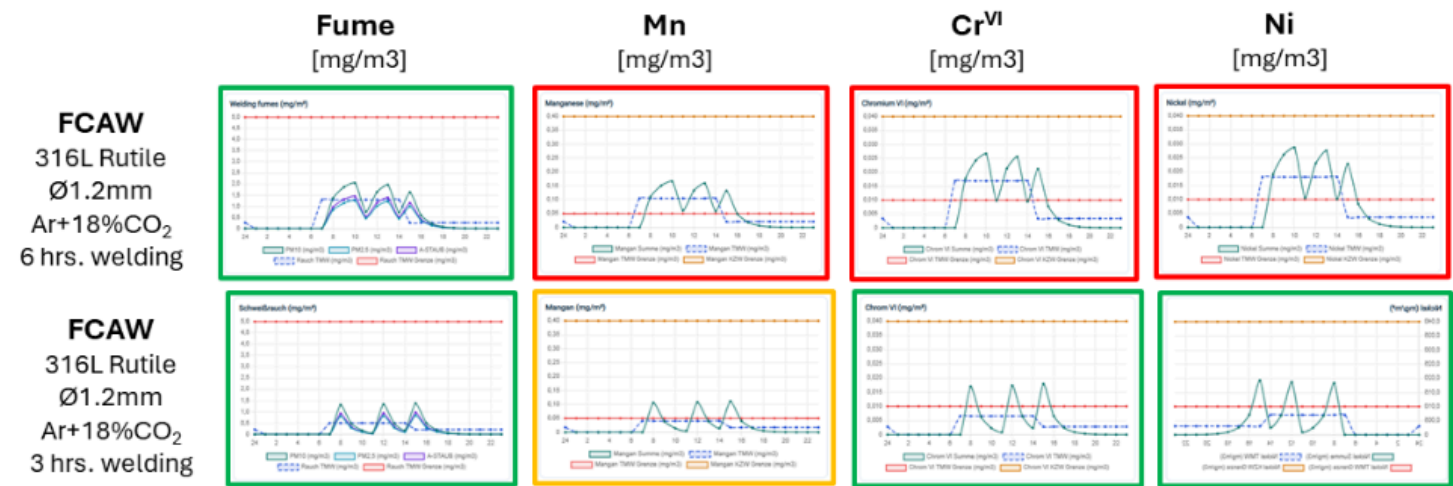


Figure 10