ABSTRACT
This work presents a multidisciplinary methodology for the identification of critical activities in an industrial process utilizing task time quantification techniques present in ergonomic analysis and involving the participation of socio-technical users. It involved an activity analysis that focused on the individual workers’ functions and behavior when carrying out their tasks in a metallurgy electrolysis unit. The choice of critical activities was based on levels of exposure to occupational, environmental and operational health risks present during the working period. The methodology identified critical activities that put both the health and safety of the workers at risk. The operators’ participatory and constructive approach reduced analytical subjectivity, providing consensual conclusions. Questionnaires were used to produce a pain map that sought to analyze the stress placed on the workers’ musculoskeletal system as a consequence of performing their activities. The quantification of time in the operator’s workday identified the criticality of exposure to occupational health risks associated with the operational procedure. A process validation was reached, which integrated a postural and kinesiological analysis with the operators’ perceptions according to their responses to questionnaires. As a result of the analysis undertaken in this work it was also possible to identify an increase in deformities present in copper cathodes and a corresponding increase in on-time activities to remove them that had led to production losses as well as worker discomfort. The methodology, which included the operators’ opinions and perceptions, concluded with a process validation. This work describes a set of proposed metrics based on ergonomic principles.

INDEX TERMS
Ergonomic work, human factors, occupational health, complex systems, task time.

I. INTRODUCTION
Ergonomics research covers two broad domains: the first involves human skills and limitations as well as human-machine system interaction, and the second involves methodologies [1]. This article demonstrates how ergonomics research can be applied to work situations and shows the transition from theory to industry practice with optimized results.

The focus of the majority of ergonomics research concerns the identification of users’ needs. It provides an analytical view with practical results to identify critical activities in the research work relating to a specific process [1].

This article focuses on occupational health problems in the electrolysis area of a metallurgical industrial unit that were subsequently analyzed by a multidisciplinary team. An increase in such operator health problems led us to investigate exposure to occupational health risks. The methodology involved the application of a process validation with
a postural and kinesiological analysis. This was compared with the opinions of the operators via their responses to specific questionnaires. It was essential that the analysis was coherent and able to ratify the identification of critical activities.

The principle aim of this work is to present a methodology for a complex system [2] based on a multidisciplinary analysis that includes planning and work schedules, as well as a quantification of time that tracks the worker’s journey, and involves the participation of users. The more specific aim was to identify critical activities within the socio-technical process that create dysfunctions that affect work safety. A process validation was added by comparing postural, kinesiological, and anthropometric analyses with a “pain map”. This map consists of physiological pain responses based on questionnaires completed by the operators of specific functions who perform the same activities, and was compared with a kinesiological analysis carried out by experts. The critical activities identified in the postural assessments provided by kinesiological analysis should be the same as the physiological pain responses from the questionnaires distributed to operators.

This article seeks to identify critical activities through dynamic interactions between the quantification of task time and the perception of operators who are working within a socio-technical process to carry out a specific task [1], [3], [4]. In this work, time quantification was considered an essential indicator for task analysis. There is a need to identify the task sequencing, and how it affects time quantification, while activity analysis, as a data collection tool, focuses on behavior during worker performance in order to meet work requirements.

Essentially, time quantification covers the operator’s working day, assists in measuring the size of the workforce, analyses exposure to occupational health risks, and facilitates the design of an appropriate layout for the time taken to relocate between tasks and also the way work is organized. In this study, causes of occupational health problems were identified due to changes in the time taken to perform tasks and the operators’ perceptions of their tasks within a Brazilian metallurgy electrolysis unit. Consequently, from a complex process analysis [2] it was possible to conclude that the increase in deformities in the copper cathodes and the increase in time activities to remove them caused production losses as well as workers’ pain and discomfort.

Johansen and Rausand [2] defined complexity as “an acknowledgement of limitations to the understanding of the socio-technical system in all its operational contexts; how risk can be assessed based on available knowledge and assumptions about system elements. An element can refer to many aspects, including individual inputs, components, processes, risks, events, conditions etc.” It is commonly believed that human performance depends on the interaction between task characteristics (for example, complexity and urgency), task executor characteristics (such as knowledge and skill), and environmental characteristics (for example, noise and temperature). Such characteristics have a significant influence on individual as well as group behavior.

Task-related research has appeared extensively in the literature for social and behavioral science, although there is limited consensus on understanding a task and its characteristics [3], [4]. Undoubtedly many tasks are becoming increasingly complex, especially those performed in safety and time-critical systems within a dynamic environment [5]. Environmental ergonomics recognizes the effects of heat and cold, vibration, noise and light on people’s health, comfort and performance. Human characteristics determine sensitivities and responses while current international standards and procedures relating to ergonomics of the physical environment attempt to assess exposure and its consequences [6], [7]. The concern is that the contribution of the time component to task complexity is often underestimated and only contemplated during critical security and time-based systems.

Human Factors conventionally considered as contributing to complexity are simultaneity and time pressure on task performance [2]. The simultaneous sequence and execution of tasks is a challenge for the executors of those tasks in respect of their coordination [8]. This simultaneity is defined mainly by the number of task objectives [9], [10]. A previous study involved a simulated nuclear power plant and found that the control crew’s performance was affected by “temporal load”, where simultaneous tasks and time pressure were important factors. Other studies [11], [12] affirmed that a simultaneity of tasks leads to increased information load, which introduces a high level of subjective complexity to the task. In moments of acute time pressure the performance of task executors worsens in respect of strategy development, information selection and decision effectiveness when compared to reduced time pressure situations. The cause of this pressure may be due to less time being available, a perceived sense of urgency or an increase in risk. The temporal aspect is highlighted in situations that need quick and accurate responses, such as critical operations and problem-solving processes. For example, some studies [10], [13], [14], [15] presented the view that increasing complexity in an action produces an increase in concentration or a requirement for behavioral control.

Temporal demand is defined as the requirement caused by time pressure, simultaneity between tasks/presentations, or other time restrictions. In this sense, an ergonomic analysis of the work undertaken is a useful methodology for improving system reliability [16]. Ergonomic Work Analysis (EWA) seeks to move beyond reports and procedures to a more global conception of production systems, changing organizational structures, concepts of technology and the way people are trained [17], [18]. The introduction of questionnaires adds real world information, involving users of the systems in a participatory and consensual way. Additional innovations in ergonomic work analyses have enabled a broader interpretation of time quantification of activities observed in the workplace, thus improving ergonomic principles. Through an interpretation of time, we can ascertain if an activity was
performed before or after another one, or if overlap occurs when activities run in parallel.

II. ERGONOMIC ANALYSIS

The principles and methods of Ergonomics [19] and Cognitive Task Analysis [20] include individual and focus group interviews with operators and other interested parties, as well as direct observation of work activities. These principles provide a detailed perspective on how people think and reason in the complex and dynamic environments that characterize real-world tasks. Human interactions such as those involving technologies, tools, working conditions, stress factors and team dynamics are revealed, as well as fundamental trade-offs that are commonplace in an operation.

An ergonomic field study observes and interviews workers in their real work environment, and follows these basic procedures: (1) analysis of existing documentation; (2) recording information when interacting with the observed actors; (3) formulating hypotheses about the possible variation in activities; (4) validation with the subjects of the study. The methodology requires direct access to professionals, specialists and experienced workers who have the tacit skills necessary for everyday work [21]. They understand how and why the work is done and can identify variability in the workers’ activities. The preliminary analysis of documentation and the field study include performance protocols, daily occurrence reports and general safety standards.

A. CONTRIBUTION OF TIME QUANTIFICATION IN ERGONOMIC ANALYSIS ACTIVITY

Work activity takes place in a temporal environment, that is, actions are inscribed in time and are conditioned by it. Professional tasks suffer from time pressure and require coordination between the participants involved. Time spent learning and acquiring experience is also important in creating competent operators. Observables are measurable, characteristic work activities and their analysis, from a temporal perspective, should seek to identify time pressures and their consequences for the activity, the impact of difficulties and incidents over time as well as the temporal variability of similar activities. By controlling time and temporal relations, it is possible to identify operational distortions in the process, such as excessive displacements. It is also possible to evaluate exposure to occupational health risks, such as noise, heat and musculoskeletal stress, as well as scale the number of employees by activity [6], [22].

Temporal analysis of observables, including typical activities such as displacements, the line of vision, communication, assumed postures and decision-making by the length of time and frequency per activity during the workday, allows us to analyze changes in layout or physical disposition, favoring accessibility and the effective use of time [23], [24]. By quantifying frequency and communication time, it is possible to identify which means of communication are the most effective and which professionals are key to facilitate work development in the operational hierarchy. This quantification method, which takes into account frequency of movements and periods involving decision-making while also respecting the operator’s line of vision, undoubtedly helps in the management of operational activities.

Dos Santos et al. [24] applied questionnaires as a structured tool to obtain information relating to topics of interest in a Brazilian offshore installation. Operators were asked, through questionnaires, to relate aspects that affected their performance, to suggest modifications, to provide information on any pain endured as a result of operational activity and to relate the time taken and muscle groups involved. The observation and application of these questionnaires help to understand the varying demands and strategies in different contexts [20]. In this way, crucial information can be obtained concerning interactions, interpretations and attitudes, while observations can be complemented and validated through interviews. In fact, the company’s organizational culture can also be observed and validated through interviews [25].

III. METHODOLOGY

The methodology employed in this work could be characterized as applied research, focusing on knowledge of a specific situation. To understand the material losses relating to an electrolyte copper plant, an investigation was carried out with the steps outlined below.

The work team included a coordinator trained in occupational safety, ergonomics and hygiene, while observation of tasks in the industrial area was carried out by safety technicians with ergonomics training. Postural assessments were performed by a physical education teacher and kinesiological analysis by a physiotherapist specializing in postural analysis.

This study is in line with Baber and Young [26] recommendations, which emphasized the need to find a way through the challenges present in working with the client’s organizational structure and doing so within the constraints of time, resources, cost, accessibility and other factors imposed by the client.

The methodology involved the creation of a work schedule to provide time-scales for performing the analytical tasks in a multidisciplinary team. This planning structured the work time, providing durations, estimated costs and the resources needed to fully execute the project. A bulletin to monitor the activities was prepared and provided to the company on a weekly basis. Observation was carried out at the evaluation site with the quantification of task times and the use of photos and video footage, in addition to the distribution of questionnaires, interviews and environmental and occupational monitoring. The material received, including time graphs and anthropometric analyses of the observed activities was distributed among physical education teachers and physiotherapy professionals, as well as occupational safety technicians who performed the postural and kinesiological analysis.

Figure 1 shows the flowchart methodology. In phase 1, the work environment was identified and mapped using an ergonomic approach, which centered on observing the activities performed. Consultations were undertaken based
FIGURE 1. Schematics of the methodology, divided into four phases: identification and mapping; specification and characterization; physical context assessment and ergonomic recommendations. For each step an integrative view was taken in order to promote a practical application of ergonomic methodology by identifying critical activities in a metallurgical electrolysis unit.

Phase 1 – Identification and mapping of the work field
- Study and analysis of the production process: technology, machines, furniture, software, etc.
- Identification of functions, activities and situations
- Identification of operating modes and process dysfunctions, preliminary survey

Phase 2 – Specification and characterization of workplace condition
- Observation and quantification of task time
- Measurement of environmental factors
- Distribution of simplified questionnaire

Phase 3 – Validation Process: Assessment of the physical context of the tasks
- Postural analysis
- Kinesiological analysis
- Dynamic and static anthropometric analysis

Phase 4 – Ergonomic recommendations and creation of a spreadsheet of critical activities with proposal of control measures and intervention priority

on pre-written documentation via operational procedures. In phase 2, which involved characterization of the work environment, an activity time quantification was carried out, which included environmental monitoring and observation of
activity sequences. In phase 3, the opinions of the operators were validated using questionnaires. The validation process can be summarized by the identification, through kinesiology, of the muscular groups involved when performing activities and in the evaluation of the criticality of the activity using the REBA postural method. In phase 4, recommendations were made based on the criteria of criticality and feasibility of implementation.

The responses to the questionnaires were collated and added to the final report carried out by the operational or administrative workers. In keeping with the norms for field evaluation, two days were allocated for observation of operational functions and one day for administrative functions. Analysis by operational function was carried out within three days. After the evaluations had been completed, a final brainstorming session between the multidisciplinary professionals enabled us to conclude the work. The methodological stages were divided into four phases, as follows, as shown in Figure 1.

**A. PHASE 1 - IDENTIFICATION AND MAPPING OF THE INDUSTRIAL PLANT PROCESSES**

Below are detailed all phases indicated in Figure 1.

1) **STUDY AND ANALYSIS OF THE PRODUCTION PROCESS: TECHNOLOGY, MACHINES, FURNITURE, SOFTWARE, ETC**

The electrolysis unit has two types of structures: a metallic one, which represents most of the external walls, and also a masonry structure that constitute the control and administration rooms. It has two floors, natural ventilation and several openings at the sides. The objective of this process is to eliminate impurities harmful to the mechanical and chemical properties of copper plates, obtaining high purity electrolytic copper by separating recoverable impurities with commercial value including gold, silver and nickel.

In summary, the process occurs when colloidal particles suspended in a liquid medium migrate under the influence of an electric field and are deposited onto an electrode. Copper coatings obtained through electrodeposition have been widely used due to their high conductivity, which have intrinsic value for a variety of industrial sectors such as the electronics, automotive, and aerospace industries [27].

From a historical point of view, the first electrodeposition (or electroplating) patent was granted to the English inventors and entrepreneurs George Richards Elkington (1801 - 1865) and Henry Elkington (1811 - 1896) in 1840 (GB 8.447: “Improvements in Coating, Covering, or Plating certain Metals”). To obtain good electrodeposition it is essential to have excellent electrochemical batteries, the first of which was produced by the Italian physicist Alessandro Giuseppe Antônio Anastásio Volta (1745 - 1827) in 1799. The first studies on electrodeposition are credited to the Scottish surgeon and chemist William Cruickshank (c.1740 - c.1811), who deposited metallic silver on zinc and metallic copper on silver in 1801.

Figure 2 identifies the electrolysis region, where the case study activities were analyzed, with the “commercial sheet circuit” area at its center. In the electrolysis operational area electrolytic reduction occurs, purifying the copper cathode, as shown schematically in Figure 2. This area contains different types of industrial equipment, such as electrolytic cells, filters, pumps, drying ovens, overhead cranes and other industry-specific machines. The purpose of this process was to eliminate harmful impurities to the mechanical and chemical properties of copper by obtaining high purity electrolytic copper, separating recoverable impurities that have commercial value, such as gold, silver and nickel. However, the process encounters many difficulties. It can be overly manual and there are risks created by adverse environmental conditions. It can be difficult to control what goes into the electrolysis process, while each process has its own modus operandi. There is often limited capacity to remove impurities and perform electrolyte purging and there is also the issue of plant stability. Responses are often slow and the process itself is somewhat outdated.

Some significant difficulties were observed during this research, including: cells at the end of their useful life; delays in the expansion of commercial production cells; lack of power in the electric bus bars; lack of reliability for current leakage in rectifier ii, as well as problems due to the inexperience of new employees.

2) **ANALYSES OF IDENTIFIED ACTIVITIES AND CHARACTERISTIC SITUATIONS**

Analysis involved direct observation, photography or video recording, quantification by observation of task time, data related to equipment, furniture, tools and work clothes, as well as the measurement of environmental factors. This was carried out on the following activities undertaken by the stripping operator who was the focus of the observation: plate packaging; selection of raw plates; PVC cleaning; plate exchange; forming, aligning and compacting packages; cleaning area; aligning cathodes and placing and removing bars from the conveyor (Figure 2). The quantification of time through observation of activities focused on the working day of a specific operator, while other colleagues who perform the same activities answered the distributed questionnaires.

3) **IDENTIFICATION OF OPERATING MODES AND PROCESS DYSFUNCTIONS: PRELIMINARY SURVEY CARRIED OUT**

The initial concern in respect of occupational health was due to the increased number of operators absent from work because of musculoskeletal problems. This was the initial trigger that led us to identify those critical activities in the electrolysis unit that would cause worker discomfort or pain (Figure 2). Through observations and interviews it was possible to confirm that a minor change in this production process was the cause of this discomfort described below.

Five stripping machine operators were interviewed and their activities were observed during the following operational shifts: 8:30 am to 4:00 pm, 4:00 pm to 12:00 am,
B. PHASE 2: SPECIFICATION AND CHARACTERIZATION OF WORKPLACE CONDITIONS

Through systematic observation of certain operator actions, it was possible to understand how, why, for what reason, and under what conditions the work activities were carried out [29]. In this stage, monitoring of the working day, to ascertain the percentages of the time taken for each activity to be carried out, was documented in the timesheet. The team consisted of a cell inspector, who inspects the electrolysis cells; the stripping operator whose function was to remove impurities in the electrolysis cells; the conditioning operator, who assists the bridge operator in conditioning the anodes in the electrolysis cells; the machine operator, who operates the process machines and the crane operator who transports the cells in the frames via the crane. The purpose of this work area was to eliminate impurities by obtaining high-quality electrolytic copper plates.

1) OBSERVING AND MAKING NOTES

Observables are the integral elements of any behavioral response that can be noted in order to describe or infer the intrinsic logic of the response. When choosing observables, aspects are considered that enable verification of whether the initial demands have been proven [23]. Conceptually, observables are measurable characteristics and properties of the work activity [24]. These include observation and evaluation of displacements, line of vision, communications, assumed postures, and decision-making by the quantification of duration and frequency throughout the working day. These data were important for the graphical representation of activities by working hours with the percentage of the time taken to complete the activity.

Displacement occurs when there is rotation in the stripping machine in one of the workstations, which causes a greater displacement on top of the cells during packing of the plates. Observation of the operator’s line of vision demonstrated the following: when the stripping operator was working on top of the cells, his/her sightline was appropriately directed as he/she was checking the positioning of the plates and looking down the whole time. This was also the case when the stripping operator was in the area of the stripping machine, selecting the copper plates. Verbal communication took place...
with the machine operator, the crane operator as well as other auxiliary operators.

2) MEASUREMENT OF ENVIRONMENTAL CONDITIONS

Using data obtained in the previous stage and based on the observables defined, the collected data was analyzed and an evaluation of working conditions was carried out. Environmental conditions were evaluated according to conditions of exposure to noise, heat, chemical agents, and light.

Parsons [6] stated that environmental ergonomics is an integral part of the discipline of ergonomics and should be seen and practiced from this perspective. It measures the influence of the physical environment on human performance during work activities.

Environmental and occupational monitoring was carried out according to current national and international legislation. The quantification of exposure time to the risk factors such as noise, heat, vibrations, application of physical force and inadequate postures, associated with the activities observed, guided the analysis of the level of occupational exposure from the perspective of health and hygiene.

In the area of environmental electrolysis, the Brazilian regulatory standards authority passed a law, (Portaria 3214, 08/06/78), establishing a code of “Unhealthy Activities and Operations” according to articles 189 - 196 of the Consolidation of Labor Laws (“Consolidação das Leis do Trabalho”, or CLT, 6514, 22/12/77). The code amended Chapter V (Occupational Safety and Medicine) of this CLT.

3) DISTRIBUTION OF SIMPLIFIED QUESTIONNAIRE AND INTERVIEWS WITH EMPLOYEES

Questionnaires and interviews were employed to obtain first-hand knowledge of the context to be analyzed through the use of focused questions. According to Dos Santos et al. [24], “questionnaires provide a structured way to obtain information related to the topics of interest”. Interviews with long-standing professionals with many years of experience provide important information concerning implemented changes.

Their responses were essential in understanding a variety of changes that have occurred over time. Such changes often remain in the collective imagination but are not incorporated into operational procedures. For this reason, the active participation of those who are integral to the system is important in reducing subjectivity in the analysis [24].

The performance of operators in respect of the reliability of systems becomes clear when they adapt predicted procedures to a real work context or when they develop original procedures (when dealing with unfamiliar situations) in a timely manner to maintain an efficient operation and ensure the safety of the industrial plant. Control activity in a batch process industry reaffirms the value of the operators in ensuring system reliability, as they are the ones who make the final decisions over plant shutdowns or decide how to arrive at the safest solution following irregular occurrences. The questionnaires yield important information to assist in the analysis and interpretation of results.

C. PHASE 3. ASSESSMENT OF THE PHYSICAL CONTEXT OF THE TASKS

1) POSTURAL ANALYSIS

Function analysis was performed according to tasks, activities, static physical load, posture, duration, and frequency, as well as postural analysis. It is important to identify the appropriate method to be applied in each case. Postural analysis of activities was performed using appropriate postural methods, following the base position for the activities performed by the operator. The REBA (Rapid Full Body Assessment) method [32] was used, as these activities require a whole-body analysis. Postural evaluations and the methods used to identify critical activities by absolute value take into consideration the critical duration of the posture when interpreting the consequences of exposure to occupational health risks [34]. Activities considered critical in the postural analysis are those that have a high indicator value and a duration that is detrimental to the health of the operator.

2) KINESIOLOGICAL ANALYSIS OF THE ACTIVITIES PERFORMED UNDER THE APPLICATION OF FORCES

Gilad [35] stated that the potential of a manual act to accumulate risk and become an occupational disorder is determined through a detailed analysis of its kinesiology. This is known as the biomechanical profile of the movement. In the context of the demands and routines of work activities, procedures were reviewed and elements involving repetitive movements also identified. Kinesiological analysis aims to evaluate the skeletal groups involved in activities considered to be critical using the postural method. The results were compared to the mapping of pain elicited from the questionnaire responses.

3) COMPARISON OF THE QUESTIONNAIRE RESULTS

The results of the postural analysis were compared to the questionnaire responses and the consequences of pain, using the Corlett and Bishop diagram [36] in addition to a kinesiology analysis of the activities (Figure 3). The identification of skeletal muscle groups is related to the consequences of pain when carrying out activities. The Corlett Diagram was published in 1976 by Esmond Nigel Corlett (1923 - 2020) and R. Bishop and consists of a semi-quantitative tool for assessing postural discomfort through a map of body regions [36].

The images of the workers’ postures considered critical must be taken at an appropriate angle to facilitate the analysis. The post-analysis postures selected from the study were classified and control measures applied.

From the pain map based on responses to the questionnaires, it was established that body parts with pain indicators presenting values less than or equal to 30% required attention; greater than 30% and less than or equal to 60% were considered critical; and greater than 60% required emergency treatment.

The purpose of this methodology was to identify the critical activities that affect the performance of the stripping operators of an electrolysis processing unit. In this phase,
an ergonomics approach based on an analysis of operators’ activities was undertaken, using tools to support the postural, anthropometric, and kinesiological analysis. The result of the integration of these analyses was compared to the pain responses according to the Corlett diagram (see Figure 3).

The operators’ perceptions included in the analysis reduced the subjectivity of the experts’ judgment. This phase can therefore be considered a process validation. Methods vary between different areas such as engineering and occupational health, and as ergonomics is multidisciplinary, the methodology adopted in this study covered the various contextual aspects, integrating analytical results and focusing on the work activity performed by the operational function. Barber and Young [26] showed the importance of validation methods that shift the focus away from subjective opinion and toward objective measures in which predictive validity of methods can be better defined.

4) DYNAMIC AND STATIC ANTHROPOMETRIC ANALYSIS
Static and dynamic anthropometric analyses seek to relate the users’ fixed and dynamic measurements in order to facilitate the performance of activities without the application of force and excessive use of skeletal muscles. It is important to design machines and equipment to meet the anthropometric measurements of human body movements, according to the spatial area of the relevant workplace in order to improve both usability of equipment and reduce musculoskeletal demands in relation to activities. It is also essential to analyze the anthropometric and biomechanical characteristics of the equipment users. Gejdos et al. [30] declared that “anthropometric and ergonomic requirements are important for the protection of health and safety in the workplace”. Realyvásquez-Vargas et al. [31] affirmed that the “anthropometric design of workstations facilitates the sustainable development of the workplace”. Accessibility is another important item that should be analyzed when assessing work task performance.

The workplace encompasses the entire physical environment that involves the worker and his actions when performing activities. It refers, therefore, to the set of equipment and installations on whose surfaces the worker supports his body and performs actions, or even the work field, such as floors, chairs, tables and benches, as well as equipment operated through instruments and tools, remote controls, computers, etc. [31].

The relationship between dynamic and static anthropometry is fundamental in order to provide angulations and movements within a comfort area without placing excessive demands on the operator’s musculature. It is therefore extremely important to analyze the task and design work spaces for regular use and maximum use, in the horizontal and vertical planes, which include the extent of arms reach and the limitations of the human anatomical structure, as well as the angulations in the joints of the musculoskeletal system and the extent of reach in the surrounding area when the limbs are extended.

Some of the basic issues relating to the analysis of work places that include (but are not limited to) physical aspects are: postures adopted by the worker (sitting, standing, specific postures, alternating postures); the layout of the immediate workplace and its surrounding area; characterization of the task; the physical environment and the organizational environment. Accessibility due to planned displacements is a further item to be analyzed in the operational context.

D. PHASE 4 - SPREADSHEET OF CRITICAL ACTIVITIES WITH CONTROL MEASURES
As explained above, ergonomic recommendations were made following a brainstorming of interdisciplinary professionals involved in the task analysis. Postural criticality and application of force depend on the operator’s exposure time. The quantification of time with observations in the workplace was important to identify inappropriate postures or applications of force.

In this work, the process of validating the results occurred when postural and kinesiological analysis coincided with physiological responses to pain in the questionnaires completed by operators who perform the same functions with the same activities. It is important to emphasize that the criticality
of musculoskeletal stress due to the application of force depends on the exposure time and the frequency of recovery pauses. It also became clear that team brainstorming was essential as it prioritized the intervention of critical activities.

The below results were presented in a spreadsheet that identified the critical activities along with relevant dysfunctional problems related to the process, as well as the postural analysis.

The methodology presented was developed since 2003 by one of us and applied to the fields of mining, metallurgy, supermarket chains, toll stations, petroleum industry, airport, tire manufacturing, as well as other manufacturing industries, such as weaving, plastic packaging etc. The focus has always been the identification of critical activities in the work production process that have an impact on workers' health.

IV. RESULTS

By observing the activities being performed and using the job timesheets, noting displacements in the physical workspace, as well as verbal communication, lines of vision, and also assessing the state of the equipment, we were able to establish the distribution of the operators’ tasks throughout a work cycle [24]. Observations were made for both the established and the newer operators. It was found that the older operators, who did not develop injuries, had regular personal and professional habits and did not change their shift routine. However, some more recently recruited workers often changed their shift patterns for personal reasons and consequently did not take the regular rest breaks inherent in the work shift system [24].

A. RESULTS OF ACTIVITY TIME QUANTIFICATION

Exposure time was also important in identifying work patterns through first-hand observations of various operators’ activities. The work time of the operators was determined by directly observing their work as well as by conducting interviews. The work shift was divided into cycles and activity time measured according to the total work time, which was 389 min for this work shift. All procedures were diligently recorded from start to finish by direct observation, employing video recording and photography [34].

The activities observed in a working day were: 1: aligning anode plates; 2: waiting for the bridge to place anode plates in the cells; 3: hitting the matrix on the rocker for alignment; 4: removing covering lid; 5: placing shim on the anode plate; 6: taking a hose to put the solution in the tank; 7: draining contacts from the matrices; 8: opening the cart by dropping cargo; 9: placing plates in the disposal; 10: removing plate metal from the machine; 11: arranging plates in the cart; 12: putting the plate on the cross conveyor by hand; 13: removing plate stuck in the machine; 14: breaking wax; 15: picking up the plate that falls to the ground when it is removed from the die; 16: removing the copper plate from the matrix using a fiber machete; 17: placing plates on the transverse transporter; 18: stripping PVC; 19: removing plate from the matrix; 20: pushing cart; 21: taking off plates; 22: watching the plates leaving the operation; 23: placing plates in the cart; 24: brushing contact; 25: removing plates from the cart; 26: releasing copper plate from stainless steel matrix with a spatula; 27: removing copper splinters from the matrix with a spatula; 28: lunch.

The percentage distribution of time accumulated in the sequence of activities observed from the stripping machine operator is presented in Figure 4.

![Figure 4. Representation of percentage of time, all activities developed by the operator during a working day shift (near 389 minutes). The number in parentheses indicates the order in which the activity was performed in the chronological sequence of the work cycle.](image-url)

The occupational environmental exposures in the work area were then analyzed. For this analysis, quantification of the execution times of each task is important in order to define the extent of occupational exposure allowed under Brazilian legislation.

B. MONITORING THE ENVIRONMENTAL CONTEXT

In keeping with the description summary presented in Figure 1, the second phase involved the measurement of environmental factors. Parsons et al. [6] declared that: “there are numerous factors that can make up a working environment. These include noise, vibration, light, heat and cold, particulates in the air, gases, air pressures, gravity, etc.” They affirmed that “the applied ergonomist must consider how these factors, in the integrated environment, will affect the human occupants” [6].

There are six main factors that should be quantified in order to assess human response to thermal environments: air temperature, radiant temperature, air velocity, humidity, the activity of the occupants, and the clothing worn by the occupants. A thermal index integrates these values in a way that will provide a single value that is related to the effects on the occupants. So, in this work was considered the specific ISO standards for the workplace, as described by Parsons et al. [6].
We referenced Brazilian environmental legislation relevant to health in the workplace once it identified that conditions present in the monitoring exceeded their environmental levels of comfort. The monitoring involved evaluating occupational exposure in relation to the performance of the work activity, using exposure time as an indicator of criticality according to the recommendations in Brazilian CLT regulatory standard 15 (cited in item about measurement of environmental conditions).

Continuous or intermittent noise levels were measured in decibels (dB) according to the A scale and Brazilian legislation and by means of a calibrated noise dosimeter. The results for each operator were: 87.0; 87.0; 88.2; 86.4 and 86.7 (in dB), with an average of 87.06 ± 0.46 dB. These results were compared with the exposure time of the operator’s shift. Monitoring required the use of hearing protection equipment, in accordance with regulatory guidelines. However, all employees were using protective headphones.

Exposure to heat was evaluated using the Wet Bulb Thermometer Globe (WBTG) as recommended by Brazilian regulations. The thermal overload index, for an indoor environment, was obtained without any solar load. Monitoring was carried out in the Commercial Electrolysis Cells Unit with the following results: 29.1°C, 30.5°C, 28.2°C and 27.9°C for the shift which ran from 08:00 to 10:00am, providing an average temperature of 28.93 ± 0.88°C. These environmental conditions exceeded recommended limits set out in the guidelines of the regulatory standard for heat exposure.

Occupational exposure to noise and heat generates a physiological response that has a clear impact on operator performance and productivity [6]. Collective or individual control measures should therefore be applied in order to reduce exposure.

In addition to the analysis of environmental impacts, questionnaires were important tools, as highlighted in the methodology by directly consulting the operators it is possible to reduce analytical subjectivity by obtaining routine information concerning the industrial area.

C. RESPONSES TO QUESTIONNAIRES COMPLETED BY THE TEAM OF OPERATORS

A participatory and constructive ergonomics approach was followed to reduce analytical subjectivity with consensual conclusions. Questionnaires (see Appendix) were distributed to the five members of each of the four operator crews. An initial questionnaire was developed and used to identify information concerning weightlifting activities, inappropriate positioning activities, and proposed modifications involving the opinions of each operator. The importance of these tools has been documented by Dos Santos et al. [24].

The activities that involve lifting weight, as related by the operators, were: selecting raw plates; placing plates on the conveyor; aligning cathodes in the receiving current; taking off raw plates; pulling the production cart and compacting the package of raw plates. The activities with the most inappropriate position were defined by the operators as: pulling production cart; anode alignment; working all day while standing; collecting splinters; compacting raw plates.

The operators’ proposed modifications to improve the industrial area were as follows: automation of the cart that supports the plate package, providing a hoist to remove the plates; resizing the edges to avoid side cuts of the boards; decreasing the walkway on the left side to facilitate PVC cleaning; improving lighting and ventilation. Importantly, the work context was analyzed according to how the operators’ themselves perceived the tasks they perform. The responses were compared with in situ analysis, as explained below, alongside other tools discussed in this work.

D. ACTIVITIES CONSIDERED CRITICAL USING THE REBA POSTURAL METHOD

The REBA (Rapid Entire Body Assessment) method was developed by Sue Hignett (b. 1961, English ergonomist) and Lynn McAtamney (c. 1963, English physiotherapist) [32] and is intended for the analysis of upper and lower limbs, the trunk and neck, taking into consideration the load or other aspects involving use of force. Analysis involves studying the integration of static and/or dynamic positions adopted by the upper limbs (arm, forearm, and hands), trunk, cervical spine and legs. By observing the activities, and analyzing the following groups: trunk, neck, legs, load, arms, forearms, and wrists, scores are assigned to produce an overall score. In the final assessment, the risk level and recommended action to mitigate the exposure is also assigned [32]. The analyses used the range of body parts found in the Group A and B diagrams from Hignett and McAtamney [32]. Both A and B scores are combined in Score C and the REBA action levels table are taken from reference [32] to enable all possible combinations and result in a REBA activity score.

By way of illustration, a REBA Excel scoring worksheet was created and can be seen in Figures 6 and 7, detailing calculations for activity 16, represented in Figure 5.

A summary of the procedure used can be seen in the following graphical representation taken from an Excel spreadsheet on the REBA method.

The REBA method [32] divides the analysis into two groups: A, referring to trunk, neck and legs, and B related to arms, forearms and wrists. In activity 16, as illustrated in Figure 5, the trunk had a flexion between 20° and 60° and an extension of greater than 20°. There was a lateral rotation inclination, resulting in a total trunk score equal to 4. The neck was in a position of flexion greater than 20° with an extension greater than 20°, without being rotated or inclined to the side. This resulted in a total neck score of 3. The legs were in a bilateral support, resulting in a leg score of 1. The integrated value of these three segments resulted in a score of 6 for Table A from ref. [32]. This integration of the Table A score added around 22lbs to the load/force, with shock or rapid growth, and this increased the A score to 9.

Activity analysis indicated a unit increase in the score due to one or more body parts being static for more than 1 minute. A further unit was added due to the activity...
The conclusion, Score C, is linked to the integration of Table A (with the added application of force, making Score A equal to 9) with that of Table B and added to the integration between arm, forearm and wrist, resulting in a B Score equal to 3 for both sides. The overall result corresponded to the C score also from ref. [32], which was derived from integrating the A and B scores with the final activity score. This resulted in the REBA 12 protocol, containing a very high risk level and the need to immediate implement corrective measures. The calculations are shown schematically in Figure 6.

REBA was chosen as the method of postural assessment [34] and was applied to the base position in the activities performed by the operator according to type of activity, static physical load, posture, duration, and frequency. The identification of critical activities by absolute value was concerned with the critical duration of the posture and with the interpretation of the consequences of exposure to occupational health risks [37]. The intervention priority indicator was the absolute value resulting from the postural analysis that defines the criticality of occupational exposure, and was adopted in this work as a criterion. Table 1 presents analytical results of the identified activities and their respective dysfunctions. The intervention priority followed the original REBA risk level [32]: 0 (negligible); 2-3 (low); 4-7 (medium); 8-10 (high); 11-15 (very high). No values above REBA 12 were observed in this work.

E. RESULTS OF THE KINESIOLOGICAL ANALYSIS

The kinesiology analysis of the critical activities using REBA [32] by the team of specialists identified muscle groups according to activity. Importantly, these muscle groups should correspond to those selected for the pain responses in the Corlett diagram (Figure 3) in the operators’ questionnaires. The kinesiological analyses of the critical activities identified using the REBA method were as follows:

- **Activity 1**: Anode plate alignment, requiring movement of the cervical, trunk and shoulder flexion and horizontal arm adduction. The muscles involved were: long head, anterior rectum and lateral of the head, anterior, middle and posterior scalene and sternocleidomastoid, psoas major and minor, abdominal rectum, internal and external oblique, serratus anterior, subscapularis, pectoralis minor, pectoralis major (superior fibers), anterior deltoid.

- **Activity 4**: Removing the large covering lid required movement of the cervical, ulnar, trunk and shoulder flexion, and humeral adduction. The muscles involved were: long head, anterior and lateral rectus of the head, anterior, middle and posterior scalene, and sternocleidomastoid; brachial, brachioradialis, biceps brachii, round pronator, long palmar, radial carpal flexor and ulnar carpal flexor; major and minor psoas, rectus abdominis, internal and external oblique, annular scapula, major and minor rhomboid, trapezius.

- **Activity 5**: Placing shim on the anode plate required cervical flexion, trunk flexion, knee flexion, shoulder flexion and shoulder extension. The muscles involved were: long head, anterior and lateral rectum, anterior, middle and posterior scalene, sternocleidomastoid, major and minor psoas, rectus abdominis, internal and the external oblique; tensor fasciae

![FIGURE 5. Example of critical activity 16. This activity produced the highest REBA value (12 for cervical, cubitus and trunk flexion, as indicated).](image-url)
**TRUNK**

| Situation               | Score | Posture adjustment | Score |
|-------------------------|-------|--------------------|-------|
| Vertical                | 1     |                    |       |
| Flexion: 0 - 20°        | 2     | If the back is    | 3     |
| Extension: 0 - 20°      |       | rotated or tilted |       |
| Flexion: 20 - 60°       | 3     | to the side: +1  |       |
| Extension: > 20°        |       |                    |       |
| Flexion: > 60°          | 4     |                    |       |
| **TOTAL TRUNK:**        | 4     |                    |       |

**ARMS (SHOULDERS)**

| Situation               | Score | Posture adjustment | Score |
|-------------------------|-------|--------------------|-------|
| Flexion: 0 - 20°        | 1     | Abducted / Rotated | 1     |
| Extension: 0 - 20°      |       | arm: +1            |       |
| Flexion: 20 - 45°       | 2     | Suspended shoulder:| 1     |
| Extension: > 20°        |       | +1                 |       |
| Flexion: 45 - 90°       | 3     |                    |       |
| Flexion: > 90°          | 4     | Supported arm: -1  |       |
| **TOTAL ARMS:**         | 1     |                    | 2     |

**NECK**

| Situation               | Score | Posture adjustment | Score |
|-------------------------|-------|--------------------|-------|
| Flexion: 0 - 20°        | 1     | If the neck is    | 2     |
| Extension: 0 - 20°      |       | rotated or tilted |       |
| Flexion: > 20°          | 2     | to the side: +1  |       |
| Extension: > 20°        |       |                    |       |
| **TOTAL NECK:**         | 3     |                    |       |

**FOREARMS (ELBOWS)**

| Situation               | Score | Posture adjustment | Score |
|-------------------------|-------|--------------------|-------|
| Flexion: 60 - 100°      | 1     | no adjustments     | 1     |
| Flexion < 60° ou        | 2     |                    | 1     |
| Flexion > 100°          |       |                    |       |
| **TOTAL FOREARMS:**     | 1     |                    | 1     |

**LEGS**

| Situation               | Score | Posture adjustment | Score |
|-------------------------|-------|--------------------|-------|
| Bilateral carrying      | 1     | Knee(s) Flexion    | 1     |
| weight: Walking;       |       | 30 - 90°: +1       |       |
| Seated                  |       | Knee(s) Flexion    |       |
| One-sided carrying      | 2     | > 60°: +2          |       |
| weight: Unstable,       |       |                    |       |
| **TOTAL LEGS:**         | 1     |                    | 1     |

**SCORE**

| Table A                | 6     |
| Table B                | 1     |
| **TOTAL LOAD / FORCE:**| 9     |

**LOAD / FORCE**

| Weight                  | Score | Situation | Score |
|-------------------------|-------|-----------|-------|
| < 5 kg (11 lb)          | 0     |           |       |
| 5 - 10 kg (11 - 22 lb)  | 2     | Shock or   | 1     |
|                         |       | rapid      |       |
|                         |       | growth: +1 |       |
| > 10 kg (22 lb)         | 2     |           |       |
| **TOTAL LOAD / FORCE:** | 3     |           |       |

**PULSES**

| Situation               | Score | Posture adjustment | Score |
|-------------------------|-------|--------------------|-------|
| Flexion: 0 - 15°        | 1     | deviated pulse /  | 1     |
| Extension: 0 - 15°      |       | twisted wrist : +1 |       |
| Flexion: > 15°          | 2     |                    |       |
| Extension: > 15°        |       |                    |       |
| **TOTAL PULSES:**       | 1     |                    | 1     |

**ARM, FOREARM AND WRIST CONNECTION**

| Good                    | 0     |
| Fair                    | 1     |
| Poor                    | 2     |
| Unsatisfactory          | 3     |
| **TOTAL COUPLING:**     | 2     |

**CONCLUSION**

| Left                   | Right   |
|------------------------|---------|
| SCORE C (Table C)      | 9       |
| ACTIVITY SCORE         | 3       |
| SCORE REBA (Score C + Activity Score ) | 12 |
| **RISK DEGREE**        | Very High |

**ACTION:** Immediate corrective measures required

**FIGURE 6.** REBA Excel scoring detailed worksheet for activity 16 considering tables A and B from reference [32].
TABLE 1. Results of the critical activities, through process dysfunctions, indicating intervention priority by means of REBA analysis [32]. Intervention priority followed the original REBA risk levels: 8-10 (high) and 11-15 (very high).

| ANALYZED ACTIVITY | INTERVENTION PRIORITY | PROCESS DYSFUNCTIONS |
|--------------------|------------------------|----------------------|
| Activity 1: Aligning anode plates | REBA 12 (VERY HIGH) | The anode alignment wrench is small due to the weight of the anode, causing the operator to stoop to perform activity |
| Activity 4: Removing large covering lid | REBA 10 (HIGH) | The operator does not have a view of the lid, so he has to keep the column tilted until he is able to remove it |
| Activity 5: Placing shim on the anode plate | REBA 12 (VERY HIGH) | The anode comes with irregularities in the rings, not giving the necessary verticality, causing the operator to lift the anode and support it, in order to achieve the necessary verticality |
| Activity 7: Draining contacts from the matrices | REBA 9 (HIGH) | When performing the activity, the operator performs light static contraction with cervical flexion and arm abduction |
| Activity 8: Opening the cart by dropping cargo | REBA 11 (VERY HIGH) | The activity of opening the rocker forces the operator to continue static contraction movements, straining the scapulohumeral joint |
| Activity 9: Placing plates in the disposal | REBA 11 (VERY HIGH) | This activity has a trunk flexion requirement |
| Activity 10: Removing plate metal from the machine | REBA 12 (VERY HIGH) | Some plates are not stripped properly due to some deformity, causing them to get stuck in the machine and the operator has to remove them |
| Activity 11: Arranging plates in the cart | REBA 11 (VERY HIGH) | The activity requires the operator to stand with the column inclined to arrange the plate on the cart |
| Activity 13: Removing plate stuck in the machine | REBA 11 (VERY HIGH) | When the plates are manually removed from the dies, they fall to the ground, causing the operator to tilt the column thereby lifting weight |
| Activity 15: Picking up the plate that falls to the ground when it is removed from the die | REBA 11 (VERY HIGH) | When the plates are manually removed from the dies, they fall to the ground, causing the operator to tilt the column with weight lifting |
| Activity 16: removing the copper plate from the matrix using fiber machete | REBA 12 (VERY HIGH) | In the activity of compacting the plates on the cart, the operator hits the plates with an iron bar, forcing him to perform movements with both arms above the shoulder line (see Figure 5) |
| Activity 17: Placing plates on the transverse transporter | REBA 8 (HIGH) | Some cells have bars smaller than others, causing them to fall during transfers, thus generating extra activity for operators who need to keep putting them back on the rail |
| Activity 18: Stripping PVC | REBA 9 (HIGH) | In the PVC removal activity, the operator holds the arm above the shoulder level in static contraction with cervical extension and shoulder flexion |
| Activity 19: Removing plate from the matrix | REBA 11 (VERY HIGH) | The machine’s suction cup is unable to strip some plates causing the operator to have to strip manually, which requires physical effort and extra activity |
| Activity 20: Pushing cart | REBA 8 (HIGH) | When the trolleys are full of plates, they are manually removed, generating a physical effort for the operator who has to push the trolley on the rail |
| Activity 21: Take off plates | REBA 9 (HIGH) | It was observed that the height of the work field is inadequate and this activity only occurs because the wax placed to prevent the plates from sticking together is not 100% effective |

latae, rectus femoris, medial and intermediate vastus lateralis; coracobrachialis, anterior deltoïd and pectoralis major (superior fibers), teres major, long head, triceps brachii, posterior deltoïd and great dorsal.

- Activity 7: Drying the contacts of the matrices required cervical flexion and abduction of the shoulder. The muscles involved were: long head, anterior rectus and lateral of the head, anterior, middle and posterior scapulae, sternocleidomastoid, major and minor teres, major and minor rhomboids, trapezius, supraspinatus and the middle and posterior anterior deltoïd.

- Activity 8: Opening the rocker by dropping cargo and releasing the load involved cervical flexion and shoulder flexion. The muscles involved were: long head, anterior rectus and lateral of the head, anterior, middle and posterior scapulae, sternocleidomastoid, coracobrachialis, anterior deltoïd and the pectoralis major (upper fibers).

- Activity 9: Placing sheets in the disposal area involved shoulder flexion. The muscles involved were: coracobrachialis, anterior deltoïd and pectoralis major (upper fibers), lumbar, thoracic and cervical interspinous, cervical, thoracic and lumbar sacrolumbar.
**TABLE 2.** Pain map with percentage answers from questionnaires provided to five stripping machine operators concerning the pain they experience (according to regions of the body) caused by the musculoskeletal requirements of the activities performed.

| Neck | Shoulders | Upper back | Arms | Back | Forearms | Lower back | Fists | Pelvis | Hands | Thighs | Knees | Legs | Ankles/feet |
|------|-----------|------------|------|------|----------|------------|------|-------|-------|--------|-------|------|------------|
| 20   | 40        | 20         | 20   | 20   | 20       | 0          | 0    | 0     | 0     | 20     | 0     | 20   | 0         |

- **Activity 10:** Removing sheet metal from the machine required trunk flexion and shoulder flexion. The muscles involved were: major and minor psoas, abdominal rectum, internal and external oblique, coracobrachial, anterior deltoid and the pectoralis major (upper fibers).

- **Activity 11:** Arranging plates on the cart required trunk and shoulder flexion. The muscles involved were: psoas major and minor, rectus abdominis, internal and external oblique, coracobrachialis, anterior deltoid and pectoralis major (upper fibers).

- **Activity 13:** Removing a plate stuck in the machine involved the abduction of the shoulder above the shoulder line, thereby forcing the joint. The muscles involved were: major and minor teres, major and minor rhomboids, trapezius, supraspinatus and the middle and the posterior anterior deltoid.

- **Activity 15:** Picking up a plate that falls on the floor when removed from the matrix required trunk flexion, shoulder flexion and cervical flexion with rotation. The muscles involved were: major and minor psoas, rectus abdominis, internal and external oblique, coracobrachialis, anterior deltoid and pectoralis major (superior fibers), long head, anterior rectum and lateral head, anterior, middle and posterior scalene and the sternocleidomastoid.

- **Activity 16:** Hitting the plates with a beater required cervical flexion, ulnar flexion, trunk and shoulder flexion. The muscles involved were: long head, anterior rectus and lateral of the head, anterior, middle and posterior scalene, sternocleidomastoid, brachial, brachioradialis, biceps brachii, round pronator, long palmar, radial carpal flexor and ulnar carpal flexor, major and minor psoas, rectus abdominis, internal and the external oblique. All analysis was based on photographs and video as illustrated in Figure 5.

- **Activity 17:** Placing plates on the transverse transporter involved a cervical extension, and ulnar and shoulder flexion. The muscles involved were: trapezius (upper fibers), transverse spinous, spinal, brachial, brachioradialis, biceps brachii, round pronator, long palmar, radial carpal flexor and ulnar carpal flexor, coracobrachialis, anterior deltoid and the pectoralis major (upper fibers).

- **Activity 18:** Stripping PVC involved cervical extension with shoulder flexion. The muscles involved were: trapezius (upper fibers), transverse, coracobrachialis, anterior deltoid and pectoralis major (upper fibers) spinous, spinal.

- **Activity 19:** Removing the plate from the matrix involved horizontal adduction of the arm and shoulder flexion. The muscles involved were: serratus anterior, subscapular, pectoralis minor, pectoralis major (upper fibers), anterior deltoid.

- **Activity 20:** Pushing the cart required trunk flexion, shoulder extension and ulnar extension. The muscles involved were: psoas major and minor, rectus abdominis, internal and external oblique, triceps brachii, anconeus and the long radial carpal extensor.

- **Activity 21:** Peeling of plates involved trunk flexion, shoulder abduction and shoulder extension. The muscles involved were: psoas major and minor, rectus abdominis, internal and external oblique, major and minor teres, major and minor rhomboids, trapezius, supra spiny and the anterior and posterior deltoid.

In summary, all activities considered critical presented musculoskeletal demands on the shoulders, indicating similarities between the postural and kinesiological assessments. The kinesiological analysis was in line with REBA methodology, serving as part of a validation process. An illustrated example can be seen in Figures 5, 6 and 7 which relate to activity 16. This is part of an integrated process analysis that represents the validation process proposed in this work.

**F. COMPARISON OF RESULTS OF POSTURAL AND KINESIOLOGICAL ANALYSIS WITH PAIN MAP**

The validation process was built with the integration, in a participatory and consensual way, of the operators, who were the de facto users of the socio-technical process. Their input was compared with the kinesiological analysis to verify if the muscle groups involved in carrying out the activities correspond to those chosen in the Corlett diagram (see Figure 3).

Table 2 presents a table of results entitled ‘Pain Map’, with the responses of five stripping machine operators to questionnaires concerning the pain they experienced according to regions of the body, caused by the musculoskeletal requirements of the activities performed. In respect of the pain map, it was established that body parts with pain indicators presenting values less or equal to 30% required attention; greater than 30% and less than or equal to 60% were considered critical; and greater than 60% required urgent corrective treatment. Tasks considered critical and relating to shoulder complaints concurred with responses to the Corlett diagram for 40% of the consulted operators.
Table 3 shows the results of the intervention priority for the critical activities related to Table 1, with reference to both the REBA results and the responses to the questionnaires.

A priority criterion per activity was adopted based on the absolute value of the REBA result, which attained a maximum of 12, indicating a high risk level [32]. In activities identified as critical, the kinesiological analysis detailed the musculoskeletal groups involved in the activity. The requirement to use the shoulder was observed in all analyzed activities, with the results shown in Table 2 where the shoulder region is perceived by the operators to be the most critical area of the body. In compiling the results of the operators’ physiological pain responses by function, we summarized the musculoskeletal requirements and compared the data to responses from previous analyses. The compatibility in the answers indicated a validation process, to be discussed later.

These activities were then considered in order of criticality prior to intervention. The anthropometric situations in the work area were then analyzed, which for many activities resulted in the ability to define the criticality of the situation.

**G. STATIC AND DYNAMIC ANTHROPOMETRIC ANALYSIS AND ACCESSIBILITY**

The workplace evaluation revealed health concerns due to anthropometric inadequacies during the principal activity in the work area, generating excessive musculoskeletal stress that was prejudicial to the operators’ health. Analysis of the execution time of the activities, and the tracking of displacements throughout the workday by time and frequency, were used to identify accessibility problems [30], [31]. The analyzes and interviews carried out identified difficulties in handling the equipment, a lack of mechanical assistance in moving weights and other handling difficulties due to the location of equipment components. This industrial site, which could be considered outdated, was not uniformly mechanized for all activities that involved lifting weights or required manually reaching, which led to a variety of dysfunctions, some of which can be observed in Table 1.

The anthropometric analysis was associated with dysfunctions present in Table 1; the REBA analysis [32]; the kinesiological observations and the responses to the questionnaires. The need for a mechanical device was identified for activities 1, 4, 9 and 21. The use of a pantographic table with height adjustment for the working area was suggested for activity 9 and the use of an adjustable platform for activity 18 was also recommended. Activity 15, which related to the removal of the plate when it fell to the ground during the removal of the matrix and activity 19, which concerned the removal of the plate from the matrix without using the suction cup that did not attach to the surface of the plates with deformities, required urgent intervention.
Suggestions for intervention in activities 5 and 17 were made for standardization or replacement of components. Automation of activities 8 and 16 was also recommended and in activities 7, 10 and 13, proposals were made to modify parts of the project. There was also the suggestion of using pantographic resources such as working height adjustment for activities 11 and 20.

The physical displacement of the stripping operator occurred in the rotation of the stripping machine workstations. In one of these stations a greater displacement was observed when the operation was carried out on top of the cells, as there was a need for manual packing of the plates. This situation occurred frequently in activity 16, as illustrated in Figure 5.

### V. DISCUSSION OF THE RESULTS

As a result of the applied methodology, critical activities and the cause of their relative dysfunctions were identified, as presented in Table 1. This was only possible by comparing the postural and kinesiological analysis with the questionnaire responses and the brainstorming of the technical team, which enabled the REBA calculation. Emphasis was given to certain critical situations presented in Table 3, according to the priority classification scheme. The criterion for intervention in critical activities followed priorities dictated by occupational health, resulting in activities 1, 5, 10 and 16 being deemed as the highest priorities. Thus, the absolute value shown in Table 2 resulting from the postural analysis was considered an indicator of intervention priority, as presented in Table 3.

All REBA results were below the maximum 15, but still significantly high, reaching a score of 12. Thus, the intention was to prioritize activities that could not be controlled by administrative measures, such as staff rotation and reduction of the execution time of activities.

The innovations presented in this study involved the use of a planning schedule that integrated observational activities in the workplace and interpretive activities with the use of tools to monitor the execution of the project. This structuring of the work and relevant studies was an important contribution to the methodology. Time was defined for workplace evaluation and for the interpretation and compilation of results by the multidisciplinary team. The quantification of time as an indicator of criticality was associated with occupational health and hygiene risks. The process of validating the results of critical activities through the integration of postural and kinesiological analysis with the physiological responses of the pain map in the operators’ questionnaires was another significant contribution to the methodology.

The stress generated by the application of force and repetitive actions due to the increase of malformations of the nodes in the cathode plates at the electrolysis basins was recognized as critical (see Figure 2). By observing this process, it could be seen that the machine’s suction cup, responsible for the removal of the copper plate from the matrix, occasionally failed to carry out the removal of the plate due to nodules that formed during the operation. The reason these nodules formed was either due to their proximity or because of the high density current that caused deposition of copper particles in the matrix, requiring the operator to remove them manually, thereby performing an extra activity using force (Table 1) that resulted in a REBA score of 11. Activity 19 refers to removing plates from the matrix. The machine’s suction cup was unable to strip some of the plates causing the operator to have to undertake this task manually, thus demanding physical effort and an extra activity. The suction cup essentially became inefficient at removing plates from the matrix due to the presence of deformities and a recommendation was made to add a mechanical aid for the displacement of the plates when suction cups could not be used. A further recommendation was to analyze the effectiveness of the suction cup and, together with the engineering department, carry out the necessary improvements.

By integrating information from the postural and kinesiological analyses, as well as responses derived from the pain questionnaire using the Corlett diagram (Figure 3), critical activities were identified (Table 1). The creation of a ‘pain map’ (Table 2) provided an overview of those activities that affected operators in the course of their work. It was possible to provide a process validation that integrated the postural and kinesiological analyses with the operators’ opinions and perceptions via their responses to questionnaires containing specific, contextual questions about their operation.

The validation process created in this study is in accordance with the statements of certain experts in the field. For
example, Stanton et al. [45] stated that: “it concerns me that this question of the validity and reliability of ergonomics methods even has to be asked, as it says quite a lot about the status of the HFE discipline.” According to Salmon et al. [38] “if, as a profession, we said we had no idea if our methods were reliable and valid then why should anyone take us seriously?”

In alignment with the four steps presented in Figure 1, when the inclusion of the operators’ opinions and perceptions and a final process validation were taken into consideration, the resulting findings were further strengthened. The questionnaires helped to understand the operators’ perspectives and form a shared knowledge base of the operating modes of the industrial area. The majority of the questionnaire responses were in line with the REBA and kinesiological analysis. Also, due to the quantification of time, it was possible to determine control measures for exposure to occupational risks such as noise, heat, and musculoskeletal requirements. In the REBA, presented in Table 1, time was a chief consideration in assessing the application of force or repetitive actions. Time quantification was also used to observe occupational health exposure to physical or chemical risks, as well as safety hazards in the process.

It is important to highlight the fact that those practical tools which target specific user groups help to facilitate the transition from ergonomic research to practice [38]. Questionnaires (see Appendix) provided a structured way to obtain information relating to topics of interest [25]. They were distributed to all operators who carry out the same function and perform the same activities and included a request for intervention proposals in order to improve the work process. The participatory and constructive approach reduced analytical subjectivity, and this was verified by REBA and kinesiological analyses, thus improving the overall analysis.

This transition of ergonomic principles from research to practice has been taking place worldwide through a series of simple and practical initiatives, and these basic, user-oriented tools will help us to understand the practical application of this discipline [1]. In this research, several interventions were made to identify the cause of the increase in occupational health issues and sub-standard product quality. In the case study, after the stainless-steel plates were replaced by titanium there was a significant reduction in the imperfections that had manifested themselves during the electrolysis process in the formation of cathode plates. It also resulted in a decrease in the need for the operators to apply force to manually remove the nodes on the plates.

In phase 1 of the methodology, as shown in Figure 1, a preliminary survey associated to the questionnaire was carried out, in order to verify changes made within the operational area and to understand the extra operational time caused by the increase in deformities in the cathode plates generated in the electrolysis process. When interviewed, the operators stated that when replacing titanium plates for less expensive stainless-steel plates, there was an increase in deformities that became detrimental to the process and a corresponding increase in tasks that placed increased musculoskeletal stress. The discovery of this productive bottleneck was made possible by quantifying time and comparing it with previous performances. Monitoring was carried out by the production team who quantified the production time as well as the quality of the final product in the electrolysis basins.

By way of an example, in Activity 17, some cells had plate bars smaller than required by the aligning mechanism, causing the cell plate to fall when it passed from the receiving to the transverse conveyor. This required an auxiliary operator to go to the transfer location for the sole purpose of manually resetting the plates. The Commercial Production Cells (CCP) had four stainless steel cell plates, each weighing an average of 30 kg, requiring the operator to apply substantial force during handling, while the titanium cell plates weigh 7 kg each. These changed cell plates increased the material deposited in the operation, making stripping of the copper plate more difficult and requiring the operator to remove them manually. From the analysis of this work, which resulted in a REBA Score of 8 (see Tables 1 and 3), it was recommended that the stainless steel plates be replaced by titanium plates, a significantly more efficient electrodeposition material.

Following the contributions of the proposed methodology, the control of time and temporal relations identified operational dysfunctions in the process, such as excessive displacements. It was possible to assess occupational health issues, such as exposure to noise and heat, as well as musculoskeletal needs, to better manage the number of employees per activity [6], [24]. Quantification of time, including frequency and duration of activities, through analysis of observables, enabled the identification of critical situations in the work process. Figure 4 presents the time of each activity which was associated with the criteria of exposure to occupational, environmental, and operational health and hygiene risks present during the working period.

The analysis of observables and measurable characteristics of typical activities from a temporal perspective is a procedure to identify time pressures, their consequences, and the impact of difficulties and incidents over time as well as the temporal variability of analogous activities. It is an important step in procedure analysis, as observed by Barber and Young [26], enabling a transition from subjective opinion to objective measures.

This study proposed linking time quantification of all activities undertaken by the operators within a working day to their exposure to occupational health and hygiene risks. The applied questionnaires had gauged the operators’ perceptions of their work relative to their observation of tasks in the workplace. The quantification of time and the use of questionnaires undertaken by operators who carried out the same activities, and were included in the observation of work activities, served to focus on the difficulties that were having an impact on production performance and the safety of
operators. It was also possible to identify the causes of these dysfunctions, as can be seen in Table 1.

Recent scientific publications have presented several methodological gaps, such as a lack of planning and understanding of organizational work, which we believe have been filled by the methodology in this study. Baber and Young [26] declared that “the experienced practitioner finds a way through the challenges of working with clients.” According to them, the objective is “to better understand ‘organizational work’ and to do this within the constraints of time, resources, costs, access, etc., that the client imposes”. Salmon et al. [38] stated that in HFE (Human factors and ergonomics) systems the research-practice gap appears to be especially prominent. Some HFE methods can be considered relatively new, e.g., Dallat et al. [39]; Hollnagell [40]; Leveson [41], [42]; Stanton et al. [43]; Vicente [44]. In this research, some relevant ergonomic issues were addressed.

This study made it possible to identify the cause of the low quality of the product as well as occupational health problems, which had led to financial losses. Hendrick [46] declared that one of the most common flaws for ergonomists is not documenting the cost-benefit of their work. One reason for this omission is the lack of an adequate methodology to measure these values. Invariably good ergonomics is good economics. The present study unveils how a complex ergonomics system can be understood in terms of a multidisciplinary analysis.

The environmental monitoring carried out showed environmental conditions to be above the level of environmental comfort. Environmental legislation relevant to unsanitary work conditions was therefore used as a guideline. Several articles highlighted the influence of environmental characteristics on human performance in activities within systems that are deemed complex due to their functions and physical structure [29]. Examples of research in different environmental contexts include noise [47], [48], [49]; heat [50]; vibration [51]; musculoskeletal demands [52], and task complexity [53].

Quantifying the time taken for activities to be carried out allows for a more comprehensive interpretation and application of effective control measures. Time was used as a criticality indicator to measure occupational health and environmental exposure. Questionnaires based on the perceptions of operators who perform the work at the industrial plant served to support control measure decisions [26]. Through questionnaires it was possible to provide updates on operating procedures from the operators’ point of view as well as certain modifications that had not been formally recognized.

When a process is predominantly managed by people, it undergoes adaptations that modify the operating modes and the time taken to carry out certain activities [54]. The interviews, aimed at professionals with many years of experience in their roles, were an opportunity to gain valuable insights into the history of the industrial work environment and how it has changed over the years.

The main contribution of this research, which was based on the observation of activities in the workplace, was the quantification of the duration of activities and the participation of users’ perceptions of the socio-technical system through questionnaires. The validation process also strengthened the analytical result.

This study also contemplated the association between different tools from the scientific and practical field of ergonomic work analysis [1], showing how interaction between the various activities can be achieved.

VI. CONCLUSION

Ergonomics seeks to understand the connections between people and all the other elements contained in a system, which can be seen as a set of interrelated or linked activities or entities (hardware, software, buildings, spaces, communities, and people) that share a common purpose, within a limited and defined context. This discipline explicitly recognizes that the system itself changes and modifies its state and its interactions, thus revealing emerging properties [19].

The purpose of this work was to identify critical activities in a socio-technical process that had created dysfunctions affecting productivity and workplace safety. A constructive and participatory methodology, with consensual results that took into consideration the socio-technical users of the system was presented. Critical activities were identified and ranked through a multidisciplinary approach, with an interpretation of results by a team of professionals from different disciplines, using integrated scientific tools and achieving validation through operators’ perceptions. It is important in ergonomics analyses to consider the quantification of time tasks and the operators’ answers based on their opinions and perceptions.

This study presents a process validation integrated with different scientific tools, comparing the postural and kinesiological analysis with a data table based on the responses to the questionnaires, known as ‘pain map’. This resulted in the analysis acquiring greater analytical reliability, thus minimizing subjectivity.

Corrective control measures were created by reformulating the hypothesis of the solution each time new dysfunctions appeared or rules developed by operators were encountered. Work that needed to be repeated, as well as production time between the process activities that increased the musculoskeletal requirements of the professionals involved, were also considered.

The definition of time according to activity allowed for the identification of occupational exposures relevant to activities appropriate to the workplace. Time observation allowed the construction of process safety control measures, taking into account the opinions of users of the socio-technical process. The context analysis, based on preliminary knowledge of the process, information exchange, and observation of the tasks of each workstation, identified the work-related problems and their causes via the study.
The importance of this study lies in the possibility of guiding ergonomists toward identifying critical activities by analyzing occupational health exposure and quantification of activity time in the working day. By choosing an industrial electrolysis plant as a study it was possible to embrace a number of diverse ergonomics procedures, and ultimately present a holistic approach to manage a variety of complex sociotechnical problems.

For example, observation of operator activities and on-site interviews quantified time per working day and provided valuable real-world information. The criterion for intervention in critical activities followed the priority of occupational health, resulting in some activities being classified as being of the highest priority. This work can be seen to have filled a gap in the literature, presenting a methodology that both identified the critical activities that impact the health of the worker and also validated the process through integrated multidisciplinary analysis.

The ability to take a global view of the process as well as being aware of interactions between the various activities is a challenge to be faced and interpreting contexts is an important line of research in this analytical process. This electrodeposition study presents a valuable example of how an integrated view based on ergonomics tools can be applied quantitatively as well as qualitatively.

**APPENDIX**
**DATA COLLECTION FOR ERGONOMIC ASSESSMENT – OPERATIONAL TASKS**

1. **NAME OF THE PROFESSIONAL:**
2. Task:
3. Age  
4. Length of service in position  
5. Basic task:  
6. Sectors previously worked in the company:  
7. Sector worked during the day:  
8. Length of working day:  
9. Equipment worked with:  
10. What activities involve movement or manual lifting?  
11. Work position? ( ) Is sitting comfortable?  
12. What is the most inappropriate position in your activity that causes discomfort or physical exertion?  
13. In your job, what would you change? ( ) Position of desk ( ) Type of desk ( ) Different chair ( ) Lighting ( ) Ventilation ( ) Minimum area per person ( ) Layout to enable movement of personnel ( ) Position of computer video monitor ( ) Another:  
14. Proposals for changes to the work area:  
15. Specify activities developed at work:  
16. When carrying out your activity, in which parts of the body do you feel pain?

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