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Original
On-site analysis of work-related stress to design workers-friendly manufacturing systems / Blandino, Graziana; Colombo, Samuele; Montagna, Francesca. - 4:(2024), pp. 205-214. (DESIGN 2024) [10.1017/pds.2024.23].

Availability:
This version is available at: 11583/2989017 since: 2024-05-27T12:58:18Z

Publisher:
Cambridge University Press

Published
DOI:10.1017/pds.2024.23

INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.23

On-site analysis of work-related stress to design workers-friendly manufacturing systems

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Abstract

Industry 4.0 is leading to technological advancement in manufacturing and causing changes in tasks performed by operators. This represents a potential trigger of humans' stress and workload. This paper aims to investigate work-related stress in an industrial environment through a real production case study through ECG, EDA, EMG, and respiratory band. From stress physiological indicators analysis, preliminary suggestions for the case study are provided to make the production system more human-centered, according to Industry 5.0. Further studies may test the effect of the recommended actions.

Keywords: human-centred design, production design, industry 4.0, case study

1. Introduction

The fourth industrial revolution has been leading to technological advancement in manufacturing by introducing automation and data monitoring systems into production systems. This change aims to monitor data and optimise the real-time efficiency of processes (Bongomin et al., 2020), but it also leads to new industrial paradigms and consequent social transformations (Oztemel and Gursev, 2020). The nature of tasks executed by operators is changing, shifting from physical to cognitive activities. Consequently, physical work intensity decreases, while the mental work for monitoring responsibility becomes burdensome (Zorzenon et al., 2022), a potential trigger of stress and workload (Michie, 2002). This risk cannot be overlooked since work-related stress severely affects workers' health status and performance. In fact, it can lead to potential chronic disorders at physical and psychological levels with consequent losses for the organisation due to workers' absence and illness (Cox and Griffiths, 1995; Hassard et al., 2018). On the other hand, stress may result in low workers' performance, decreasing production efficiency (Edú-valsania et al., 2022).

These reflections are leading to the fifth industrial revolution, laying the foundations for a human-centred industry (Huang et al., 2022), deserving deep studies in industrial environments to investigate the nature and features of human factors, mitigate negative implications, and suggest measures to contrast human risks. Besides, these elements involve the design of innovative production systems with particular attention to human well-being since the features of the manufacturing system significantly correlate with the operator's stress status. It could call for corrective actions, also contributing to the social and economic sustainability of manufacturing companies.

Beyond more traditional efforts (such as Madeleine et al., 1998), only a small number of academic publications currently aim to cope with these challenges taking into consideration objective factors including cross-analysis of psychological, physical and physiological techniques (Abd Elgawad et al., 2023), moving beyond the laboratory experimental conditions (Blandino, 2023). The main limitations of the previous studies are the non-objective measurements, mostly collected through surveys with self-assessment bias (Razavi, 2001), the data collection and analysis reliability (Abd Elgawad et al., 2023), and the experimental conditions, which as laboratories are far from real environments (Blandino, 2023). This paper aims to contribute to this forward-looking research stream by investigating work-related stress in an industrial environment through an on-site experimental activity in a real production case study. Specifically, the paper focuses on stress-related physiological data to explore the following research questions (RQs):

- RQ1: Are identifiable activities that represent the main causes of higher stress intensity to the worker?
- RQ2: What design actions may be implemented in the production system to mitigate such stress causes?

To answer RQ1, the paper presents a case study in which electrocardiogram (ECG), electrodermal activity (EDA), electromyography (EMG) and respiration rate (RSP) were monitored. The adopted experimental protocol for the case study was validated by Apraiz et al. (2023) within the EITM-funded NO-STRESS project. This choice is justified because it represents a unique case in the literature of stress investigation in real manufacturing contexts. From that validation, answering RQ2 represents a preliminary attempt (not yet statistically validated) to translate the physiological results into design and operational solutions according to the framework by Vijayakumar et al. (2022) to mitigate human stress in production systems. Hence, the study has a preliminary purpose of validating the application of workers' stress intensity, among the possible physiological measures, and the design and operational variables considered by Vijayakumar et al. (2022) in designing human-centred production systems.

This paper consists of four sections. The first illustrates literature review evidence about human-centred manufacturing, work-related stress and the research methods adopted. In addition, the fundamentals of designing human-centred manufacturing systems are deepened. The methodology section describes the experimental method phases and the equipment adopted in the case study. Then, the results are shown and measures to mitigate stress are illustrated. Finally, limitations and future directions are summarized.

2. Literature review

2.1. Toward human-centred manufacturing environments

Industry 5.0 represents the conceptual and chronological prolongation of Industry 4.0 by merging its technological orientation with the human-centricity, sustainability and resilience dimensions (Alves et al., 2023). The intelligent machines integration in production processes, in fact, increases the automation of even more customer-oriented processes (Moller et al., 2022) and it involves the hybridization of technology with humans, somehow subordinating workers to technology (Zizic et al., 2022).

Therefore, a deep reflection on the human role in the industrial sector has been emerging. Industry 5.0 aims to analyse human roles in factories through these new technologies. The focus has been moving on what technology can do for humans (Breque et al., 2021), on human-robot collaboration (Leng et al., 2022), on the comprehension of human factors (Gladysz et al., 2023), human needs (Gualtieri et al., 2022) and finding practical application of such human-factor principles (Leng et al., 2022).

2.2. Work-related stress in manufacturing

According to Palmer and Cooper (2004), workers experience stress when work demand overtakes their capability to satisfy such requests. Work-related stress occurs besides mental stress as a mental condition of humans (as specified by ISO 10075-1), also due to external influences (ISO, 2017).

Work-related stress appears to be relevant: in 2020, a survey involving workers from different countries revealed that at least 43% of them had been perceiving stress, and unfortunately, the trend has been growing by 10% compared to 2010 (Gallup Inc., 2023).

Specifically in manufacturing contexts, work-related stress has several consequences on workers' psychological, physiological, and physical health status and performance, as depicted in the Model of Work Stress (Palmer and Cooper, 2004). At the psychological level, individuals show irritability, and negative impact on memory and attention, affecting their social aspect or leading to disorders such as burnout and depression (Cox and Griffiths, 1995; Edú-valsania et al., 2022). Physiological effects may compromise unconscious processes, such as heart and brain activity, temperature, sweat secretion, and respiration (Giannakakis et al., 2022; Setz et al., 2010). Then, physical effects, e.g., musculoskeletal disorders, can be due to task factors such as posture, force, and repetition (Kee and Lee, 2012).

In the workplace, this phenomenon can cause an increase in human errors (Jian Ai Yeow et al., 2014) and distractions (Wenzlaff et al., 1988), affecting the effectiveness and quality of individual performance (Savery Head and Luks, 2001). This problem cannot be overlooked since, according to Eurostat, 2.4 million accidents at work occurred in the European Union in 2018 (McCarthy, 2021).

These elements impact the economic sustainability and efficiency of companies. Presenteeism increases stress-related errors and accidents at work and reduces companies' productivity, with higher costs for organizations (Hassard et al., 2018). As well as, chronic work-related stress disorders and accidents cause illness and absenteeism, leading to a high rate of staff turnover (Palmer and Cooper, 2004).

2.3. Stress evaluation

Traditionally, stress has been studied at the psychological level through subjective measuring, by administering standard questionnaires to workers (Zoni and Lucchini, 2012). Among the most adopted questionnaires, the Subjective Workload Assessment Technique (SWAT) investigates time, mental load and psychological stress (Arkouli et al., 2022). The Short Stress State Questionnaire (SSSQ) asks about perceptions of task engagement, distress and worry (Gualtieri et al., 2022). The National Aeronautics and Space Administration-Task Load Index (NASA-TLX) questionnaire explores mental, physical and temporal demand, performance, effort and frustration (Peruzzini et al., 2020). These subjective methods lead workers express their stress perceptions through the questionnaires, enhancing the psychological investigation of this phenomenon, but only from a self-assessment standpoint (Razavi, 2001).

However, the need for more objective measurements has emerged in the literature (Grassini and Laumann, 2020). In view of that, objective measures involving physical and physiological measurements have been increasingly adopted. Postural consequences, for instance, are studied through techniques, such as the Ovako working-posture analysis system (OWAS), Rapid Upper Limb Assessment (RULA), and Rapid Entire Body Assessment (REBA), which measure body section positions quantitatively and calculate a score proportioned to the postural risk of the subject (Peruzzini et al., 2020). In view of the specific neurophysiological processes involuntary activated as a subject's stress response (Giannakakis et al., 2022), researchers have involved physiological measurements in evaluating this phenomenon in manufacturing contexts (e.g., Peruzzini et al., 2020).

Among physiological measurements, cardiac activity, recorded through the ECG technique, is directly influenced by the activation of the sympathetic nervous system (SNS) in response to a stressful event. In such cases, cardiac activity supports the body's reactivity to the events by supplying organ and skeletal muscle cells with oxygen (Giannakakis et al., 2022). SNS also regulates sweat glands' activity, causing a proportional increase in sweat secretion in response to stressful stimuli, generating an electrical flow through the skin defined as EDA (Setz et al., 2010). Finally, emotional arousal and stress affect respiration and muscular activity, which increase breath rate and muscle tension. The physiological signal that records the action potentials of stress is defined as EMG (Giannakakis et al., 2022).

The main limits of these physiological measures are the environmental conditions where they are collected (Balasubramanian et al., 2009) and the complex correlation between psychological perception and physiological reactions (Papetti et al., 2020). Only real settings (Blandino et al., 2023) and the combination of such psychological, physical, and physiological techniques with cross-analysis of evidence may improve the reliability of stress detection since it helps researchers to get a clearer picture of humans' activations and responses (Abd Elgawad et al., 2023).

Apraiz et al. (2023) developed the protocol adopted for this contribution within the NO-STRESS Manufacturing project funded by EITM. It combines stress measures for real manufacturing context, representing one of the first methodological attempts in the literature.

2.4. Design of human-centred manufacturing systems

The production systems design aims to define how resources can be transformed into products/services considering the production plant, process inputs and working resources constraints (Zelenović, 1982).

Traditionally, production systems design has been considered a complex task since it has to consider multiple aspects related to production and the interdependency among the subsystems involved in the production (Alfieri et al., 2013; Mahmood and Montagna, 2013). Furthermore, nowadays, the design action has been facing further increased complexity: first, because of the integration of multiple technological tools, such as Augmented and Virtual Reality, Artificial Intelligence and Big-Data systems (Hane Hagström et al., 2023) that are leading to a profound transformation in the operational procedures; then, since, according to Industry 5.0 paradigm, people are going to represent the core of production processes (Wang et al., 2024). Consequently, the design of production systems cannot neglect human factors that could be affected by such design actions.

In view of that, the framework of Vijayakumar et al. (2022) embodies a first conceptual attempt to design human-centred systems. Figure 1 offers an overview of the elements (process, setting and technology, yellow layer) that must be chosen in the design of a manufacturing system and the link they have with the operational level (orange layer, tasks, operational policies, and tools). Both levels must be considered simultaneously, as they influence each other: design-level decisions affect human factors that operative practices may mitigate; on the opposite, choices at the operational level may affect production system performance, contradicting what is expected by the design level.

Figure 1. Production process design framework (Vijayakumar et al., 2022)

In this context, the physiological measures could provide a complementary view at the individual level, for example, considering the intensity of stress the worker perceives during task execution. The impact of design actions on system setting (i.e., push/pull systems), processes (e.g., layout and machinery), and technology (e.g., collaboration technologies) could be revised, given their effect at the individual level. Potential actions at the operational level (e.g., rethinking production policies or workstation equipment) can be adopted to mitigate the effects of design solutions on workers and improve their performance.

Hence, this paper does not represent the design of systems after the physiological data analysis, but rather methodologically illustrates how these measures can be integrated into the Vijayakumar et al. (2022) framework to introduce human factors in the analysis and design of a manufacturing system.

3. Methodology

A case study is here presented to investigate the compatibility of Vijayakumar et al. (2022) framework with physiological measures. Specifically, the study has a totally preliminary purpose (not yet with statistical value) of validating the application possibility of workers' stress intensity, among the physiological measures possible. This validation is conducted through an experimental campaign in a real on-site industrial environment, to ensure the reliability required by the literature (as stated in section 2.3), but it represents almost a unique case in the literature.

The adopted experimental protocol (Apraiz et al., 2023; Blandino et al., 2023) was chosen since it is suitable for real manufacturing contexts and integrates different physiological measures. Heart Rate (HR) for heart activity, Skin Conductance Response (SCR) for EDA, Respiration Rate (RSP) and Mean frequency (MNF) of the EMG signal were extrapolated as stress indicators. The protocol consists of two phases: the experimental protocol and post-experimental analysis, as in Figure 2. First, in the experimental protocol phase, the participant signed the consent form and filled out a questionnaire to collect sociodemographic data and health status information, because they could affect physiological parameters and reactions, and psychological perception. Then, the non-invasive biomedical devices were placed for calibration and the participant was instructed on the experimental procedure. During task execution, physiological signals were recorded. At half-task, a questionnaire on real-time perception was verbally administered. After the task, biomedical devices were removed and a rest pause was ensured for the subject who answered an ex-post stress questionnaire, reflecting on the task execution perceptions. This questionnaire represents a revised version of NASA-TLX.

Figure 2. Workflow

ECG was recorded through two electrodes wrists and one on the left forearm. Ring sensors were positioned in the index and middle fingers of the left hand for EDA, while the band sensor for respiratory activity was placed on the worker's abdomen. Finally, two EMG electrodes were applied near the left elbow, while the reference electrode was near the right elbow. Electrodes and sensors were linked to the central unit Encephalan Mini ABP-10, associated with the Encephalan-EEGR Elite software.

In the post-experiment analysis phase, the physiological signals were filtered and stress indicators were analysed on MATLAB. The mean value of each indicator per activity (in Table 1) was calculated and compared to the mean value in the rest condition, defined as baseline. Successively, results were cross analysed to identify similarities in the stress perceived in each activity. Generally, HR, SCR and RSP are expected to increase in stress conditions (Giannakakis et al., 2022), while MNF decreases (Petrofsky and Lind, 1980). Finally, the results provided valuable insight into the production system design.

4. Example of stress intensity investigation in production activities

Experiments were conducted in an SME operating in the plastic components industry. The analysis of data here reported includes as a participant the only worker responsible for the analysed task. Then, the paper reflects on the preliminary results from physiological data to conceive potential solutions for improving workers' well-being at manufacturing workplaces, which cannot be generalized in absolute values. Individual variation among activities is discussed, representing a comparison with a baseline activation trend. On the other hand, questionnaires were administered to combine socio-demographic and psychological data with physiological measures, but their focus on the entire task and not on individual activities and the sample dimension did not provide valuable assessments for this analysis.

Three sessions were recorded in one day to overcome signals' alteration due to the worker's sensibility to the experimental condition. Therefore, data related to each activity in the three sessions was averaged. Each data collection session lasted 18 minutes, with almost 3 minutes of rest and 15 minutes of task execution conditions, as in Brunzini et al. (2021). The experimental task consisted of assembling customized heating radiator covers by performing the activities listed in Table 1. The dimensions of the heating radiator cover were variable since it depended on the customer's order. The maximum weight per heating radiator cover was 10 kg, and the takt time for 1 m^2 surface final product was 20 minutes. The environmental temperature was around 18°C, while the worker wore earplugs for noise protection.

Table 1. List of activities

Activity code	Task activities	Work Station
A1	Initial rest period	-
A2	Manual customers' order and tube measures check	Station 1 (S1)
A3	Cutting tubes with working machine support	Resource 2 (R2)
A4	Drilling tubes with working machine support	Resource 3 (R3)
A5	Manual assembling of the heating radiator cover	Station 1 (S1)
A6	Manual packaging and labelling	Station 1 (S1)
A7	Break	-
A8	Casual error (components dropped on the ground)	Station 1 (S1)

As in Figure 3.a, the worker was required to move among workstations, preserving a high concentration. He was free to sequence the activities, whose average duration is in Figure 3.b, without restrictions on time nor working goals, as his daily normal workflow routines. In addition, the buffers between workstations were unlimited, but constrained by the reduced available physical space.

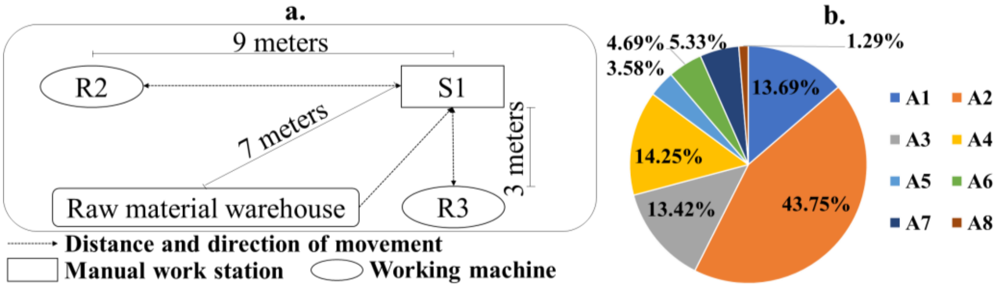

Figure 3. a. Production layout; b. Activity duration distribution

Before discussions, it is worth noting that the reliability of collected data was confirmed by coherence in the baseline A1 and the break A7 indicators since both reflect a relaxed status of workers (e.g., the resting physiological parameters of an average adult and the recovering rest after activity performance). HR showed its maximum in A4, reaching 72.64 bpm, a considerable increase compared to the participant's baseline (A1, in Figure 4.a). Compared again to A1, A2, and A6 demonstrated increased values of more than 10%, 67.52 bpm, and 66.55 bpm, respectively, reporting a higher risk exposure or a cognitive effort that could induce a notable physiological response.

About SCR, in Figure 4.b, the activities with higher values were A2, A4, and A6, with 723.46 µS, 653.63 µS and 578.29 µS, respectively. They were substantially higher than A1, with 276.14 µS. Generally, high SCR values were consistent with HR values, indicating increased SNS activity and reflecting heightened emotional or stress responses (Setz et al., 2010; Giannakakis et al., 2022).

RSP in Figure 4.c was again reliable with the previous measures about A6, which showed its peak with an RSP at 0.309 Hz. The other activities with the highest values were A5 at 0.283 Hz, A3 at 0.275 Hz, and A2 at 2.70 Hz. A decreased RSP, even more than the baseline A1, was detected during the break (A7). This could relate to humans' attitude to deep breathing as an automatism for relaxing after a physical/psychological effort (Russo et al., 2017) or to stress/anxiety for activities performed/performed (Giannakakis et al., 2022). That is evident in A3 and A5, but much less in A6 and not in A2.

In addition, MNF analysis in Figure 4.d, showed a negative peak at 15.71 Hz in A6. The other two peaks occur for A7 (18.02 Hz) and A4 (18.86 Hz). These may indicate increasing muscle tension due to fatigue or effort. The negative peak in A7 may be due to the muscle tension recovery, which is longer than the other measures here. Indeed, A7 is affected by A6, showing a negative 'heredity effect'. In addition, all the activities coherently show lower MNF values than the baseline, which may indicate a general state. Finally, A8 stress indicators were expected to increase, while it was not observed probably due to the slight magnitude of the error which was quickly fixed.

Although the analysis of the physiological activations must not be generalised, it leads to a valuable understanding of the operators' perception of the industrial environment that can be used to integrate the framework of Vijayakumar et al. (2022). In particular:

- Tubes drilling (A4) shows psychological pressure and higher stress perceived due to the impossibility of recovering the raw materials in case of error. It is not generalisable as the most stressful activity, due to the discrepancy between RSP and the other physiological signals;
- Manual packaging and labelling (A6) seem to cause a higher stress perception due to physical and psychological involvement and high responsibility. No further checks are expected once the product is stocked and potential mistakes may induce psychological pressure in the operator;
- A7 signals highlight breaks relevance during task execution to recover fatigue, increasing MNF;
- Casual error (A8) did not show high stress intensity;
- Manual check (A2) and assembling (A5) may reduce mental pressure since eventual errors can be easily fixed.

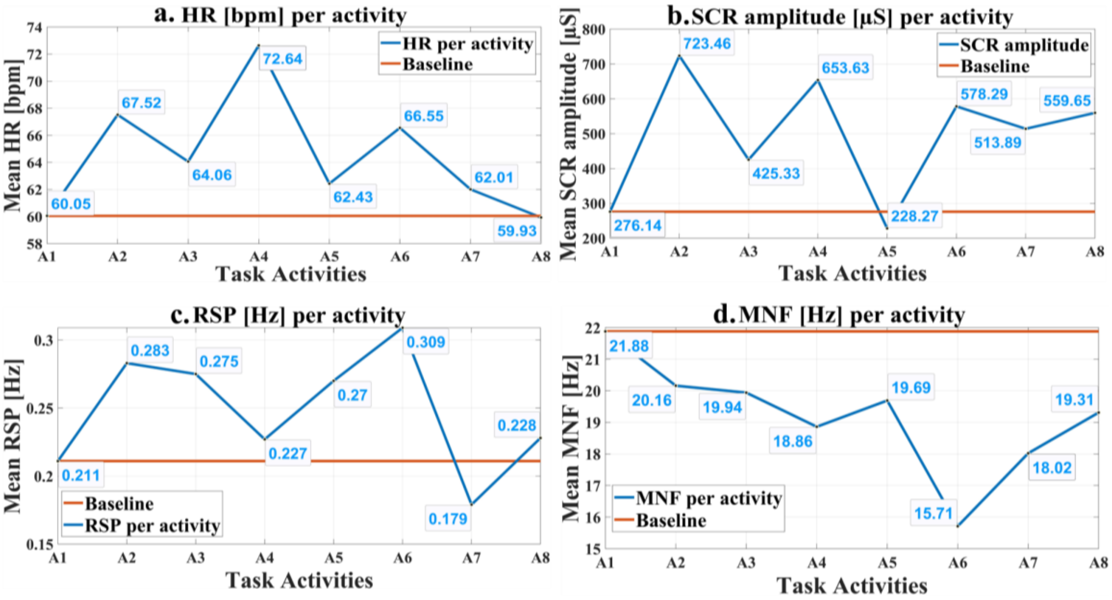

Figure 4. a. Heart rate; b. Skin conductance response; c. Respiration rate; d. Mean frequency

5. How to apply stress intensity into a design framework

The previous discussion lists variables for the production systems design. Some confirm the previous literature; they represent the first experimental validation in an industrial context with objective measures since stress was previously investigated through subjective measures or in the laboratory. Other measures emerged as preliminary insights due to recent changes in manufacturing systems.

Moreover, the worker had a central role in the design framework, in Figure 5. Indeed, the physiological signals highlighted A6 as the most critical activity and guided the framework design to mitigate stress intensity. For the system design level (yellow layer), the first variable is flexibility in task duration. When the manufacturing process allows it, flexible duration of tasks adapt the working sequences to operators' physical and psychological needs. This is suggested from the literature (Zelenović, 1982), as highlighted in the case study. The worker balanced the mental demanding activity duration (A2, 43.75% of total duration, cause of high level of SCR and low level of MNF) with the less stressful activities (A3, A4, A5, A6: total duration 35.94%). Then, microbreaks must be considered for the most stressful activities since they may help workers maintain high alertness during the work shift, with reduced accident probability (Mijović et al., 2015). Finally, the final break (A7) had a beneficial and recovering effect by reducing HR, SCR and increasing MNF. Here, RSP shows a negative peak, lower than the baseline, which can be due to internal attention control and reduced physical activity (Kral et al., 2023). In the system setting, temperatures lower than 10^{0}C or higher than 32.2^{0}C should be avoided since they decrease manual dexterity (Chao et al., 2013), reducing productivity. Noises at 4 kHz may cause hearing loss and non-auditory effects, such as accelerated heartbeat and fatigue (Chao et al., 2013).

Furthermore, the distance between workstations and their ergonomic design seems to affect fatigue. Currently, A3 and A4 require repetitive transfers among workstations, exposing operators to errors and low attention (Jian Ai Yeow et al., 2014). The workstations' position may be changed; e.g. in Figure 3.a, R2 may be moved near to S1, to minimize distance. Equally, ergonomic workstations may allow dynamic postures to prevent fatigue and effects on the MNF parameter (Balasubramanian et al., 2009). In addition, supportive technologies may guarantee safety and interaction flexibility to fit operators' needs and production changes (Fletcher et al., 2020). For instance, collaborative robots to recover raw materials from the warehouse to avoid lifting weights at long distances may support workers in demanding activities (Khan and Pope-Ford, 2015). This measure, associated with soft surfaces on the workspace floor, may reduce muscle fatigue and unpleasantness perception (Madeleine et al., 1998).

Such variables should be integrated into practices and policies at the operational level (orange layer). For instance, reducing the weight worker systematically loads for A6, preventing shoulder and back disorders (Khan and Pope-Ford, 2015) or considering that the assembly sequence is repeated throughout the working day by the operator while standing. Workers may wear appropriate equipment, such as shoes and socks, to prevent risks due to standing for long periods (Waters and Dick, 2015). Finally, the most ergonomic activities sequence may be defined and suggested to the workers (Arkouli et al., 2022).

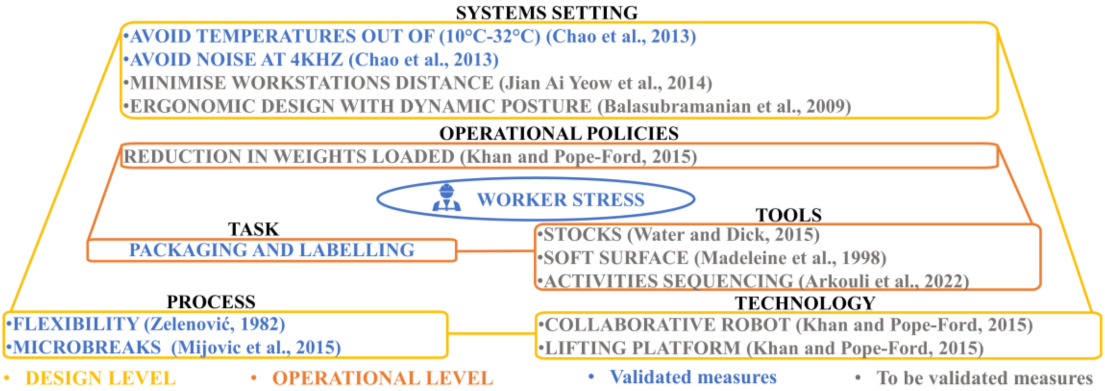

Figure 5. Revisited framework in view of the individual level

6. Conclusions, limits and future directions

This paper shows preliminary physiological results to design potential solutions to improve workers' well-being at manufacturing workplaces. The data analysis revealed that the participant perceived higher stress while manual packaging and labelling. This result cannot be generalised, but it leads to a valuable understanding of the worker's perceptions to be integrated into the Vijayakumar et al. (2022) framework. Specifically, the discussion shows some variables to consider in the production system design. Some represent a preliminary validation in an industrial environment with objective measures since stress was previously investigated through subjective measures or in the laboratory. Other measures represent insights that emerged as preliminary due to the changes in manufacturing systems in recent years.

Finally, future experiments will involve a large sample of participants, generalizing on workers' stress causes to guide designing human-centred manufacturing systems design.

Acknowledgment

The activities described in this paper have been conducted as part of the project No-Stress Manufacturing (application ID 23472) submitted to and funded by EIT Manufacturing within the second Call for Innovation activities for the Business Plan 2023 – 2025.

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