# Exploring operators' subjective well-being in interaction with advanced production technologies: A protocol study for mixed-method cross-sectional analysis in manufacturing 5.0

Giulia Bassi, Valeria Orso, Silvia Salcuni, Luciano Gamberini

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# Exploring operators' subjective well-being in interaction with advanced production technologies: A protocol study for mixed-method cross-sectional analysis in manufacturing 5.0

Giulia Bassi[1] PhD; Valeria Orso[1] PhD; Silvia Salcuni[1] Prof Dr; Luciano Gamberini[1] Prof Dr

[1]via Venezia 12 University of Padua PADOVA IT

**Corresponding Author:**
Valeria Orso PhD
via Venezia 12
University of Padua
via Venezia 12
PADOVA
IT

## Abstract

**Background:** Human-robot interaction (HRI) and collaboration (HRC) have gained significant attention in the context of advanced production technologies, especially concerning trust and acceptance. However, the investigation of the subjective well-being of operators working with these technologies in manufacturing companies has been largely overlooked. Moreover, previous research mostly relied on a single data-collection method, either quantitative or qualitative, thereby failing to capture a rich picture of their cognitive and affective states.

**Objective:** This cross-sectional study protocol aims to fill that gap by examining operators' subjective well-being, considering both cognitive (work-related quality of life and satisfaction with life) and affective (anxiety, depression, and stress) components of those who work with advanced production technologies in manufacturing companies.

**Methods:** We adopt a mixed-method approach, incorporating both quantitative and qualitative data collection techniques. Quantitative data will be gathered via a digital survey containing self-report questionnaires assessing operators' subjective well-being (cognitive and affective), fluency in HRI, and negative attitudes towards advanced production technologies. A path analysis will be performed to explore the multiple mediating roles of fluency in HRI and negative attitudes towards such technologies between cognitive and affective well-being. We further qualitatively investigate the operators' direct experiences in HRI and HRC using semi-structured audio-recorded interviews. A thematic analysis relying on text-mining techniques will then be conducted to explore operators' textual data.

**Results:** We expect that fluency in HRI may act as a protective factor for operators' affective well-being while negative attitudes toward advanced production technologies may contribute to the development or worsening of operators' psychological distress. Additionally, the integrated interpretation of both the quantitative and qualitative data collected will generate a consensus report, which will aim to serve as a practical framework for guiding workplace policies and training programs meant to foster subjective well-being and effective HRI.

**Conclusions:** Embracing one of the fundamental pillars of Industry 5.0—human-centricity—, by detecting potential psychological issues early, organizations can create a workplace that prioritizes the well-being of operators. Early recognition and prevention are crucial to promoting operators' mental well-being involved in HRI and HRC

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# Original Manuscript

# Protocol study

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**Keywords:** affective well-being; work-related quality of life; fluency; human-robot interaction; operators; Industry 5.0; protocol study

## Introduction

In the last decades, the world of work has undergone radical changes across various sectors thanks to the rapid advancements of technological innovations. Technologies, such as the Internet of Things (IoT) and cloud computing, have revolutionized how work is performed. In particular, according to the vision framed by the paradigm of Industry 4.0, the automatization of the production processes would have significantly relieved workers from the heaviest and most tiring tasks [1]. However, the strong technology-driven focus of Industry 4.0 became soon evident along with the limited accomplishment of the initial resolutions [2]. Indeed, the research that was carried out in this context sparsely focused on human factors [3]. The limitations and the need to broaden the scope of Industry 4.0 pushed for a revision of the paradigm, ultimately leading to the sprout of Industry 5.0 [e.g., 4]. According to a recent document published by the European Union [5], Industry 5.0 builds upon Industry 4.0 and it is based on three founding pillars: human-centricity, sustainability, and resilience. Importantly, this shift reflects the recognition of the need to bring workers to the forefront of the innovation process, thereby designing and implementing technologies that meet their skills and needs. The emphasis on workers is not limited to providing them with the necessary competencies in using and interacting with novel advanced production technologies. It further includes a holistic approach that prioritizes their physical and subjective well-being. In particular, this paradigm shift recognizes that workers' physical and subjective well-being are integral to sustainable productivity and innovation. In the framework of Industry 5.0, several studies have investigated specific aspects related to the impact of novel technology on the interaction between human and the technology itself, e.g., technology acceptance [e.g., 6], trust [e.g., 7], and best practices for introducing this technology [8]. The quality of this interaction often depends on fluency, a construct that captures the smoothness and synchronization between human and robotic actions. Specifically, fluency reflects the seamless coordination between humans and robots during shared tasks and encompasses different dimensions, such as human-oriented fluency, robot-oriented fluency, and team-oriented fluency [9]. Higher levels of fluency are associated with increased trust in robots, improved teamwork, and reduced cognitive workload, thereby providing a more positive experience for workers [10]. Conversely, negative attitudes towards robotic systems, including both emotional responses (e.g., discomfort, fear) and social perceptions (e.g., perceived peer or organizational support), can act as significant barriers to successful human-robot interaction (HRI) [11]. These attitudes are often shaped by workers' concerns about job security, lack of familiarity with technology, or perceptions of robots as competitors rather than collaborators [12, 13]. Addressing these emotional and social dynamics is crucial for creating a balanced and supportive work environment where advanced technologies can be effectively integrated. Additionally, a growing body of research has addressed the potential threat that novel technologies can represent for workers, because of the possibility of job loss [11] and consequently have tried to identify the factors that can lead to their smooth introduction and integration [14]. However, previous research has mainly overlooked operators' affective and cognitive well-being, especially in the manufacturing sectors [15], and how their relationship with advanced production technologies, especially robotic systems, begins and unfolds over time, and whether and how this can have an impact on their subjective well-being and social relationships. Previous research addressing the manufacturing industry mainly focused on the health risks related to physical interaction with technology, thereby failing to explore the psychosocial aspects implied and emerging from such interaction [16], with very few exceptions [17]. Moreover, in this novel paradigm, the home-work balance emerges as a crucial element [18], because it intertwines organizational and intrapersonal factors that can influence both affective and cognitive well-being. Recognizing and harmonizing these aspects is pivotal since they can not only enhance workers' job satisfaction and productivity [19] but also may be able to promote satisfaction with life and a healthier and more sustainable work environment. Job satisfaction is defined as "a pleasurable or positive emotional state resulting from the appraisal of one's job or job experiences" [20]. It encompasses a variety of dimensions that contribute to an individual's overall contentment with their professional role. One significant dimension is the home-work interface, which plays a pivotal role in determining job satisfaction by influencing the interplay between professional responsibilities and personal life [21]. This balance not only affects employees' subjective well-being and productivity but also contributes to long-term career satisfaction and organizational commitment [21,22]. In the present work, we will focus on operators' perceptions in interacting with advanced production technologies in order to investigate their affective well-being (i.e., anxiety, depression, and stress symptoms) along with their cognitive well-being, including satisfaction with life and the work-related quality of life (WRQoL) dimensions (i.e., job and career satisfaction and home-work interface) in the context of human-robot interaction (HRI) and human-robot collaboration (HRC) in manufacturing 5.0.

## Literature review

*State of the art of research investigating operators' subjective well-being in HRI and HRC manufacturing industries*

The integration of new technologies in manufacturing industries not only revolutionizes production practices but also introduces complex dynamics that can have an impact on operators' mental health [23]. Previous research conducted both with workers from manufacturing and other industrial sectors, has pointed out that work-related stress symptoms, which represent one of the most frequently examined and addressed psychological issues, have been linked to various factors, including job insecurity, high physical and cognitive workloads, and work intensity [24-26]. While stress symptoms may be a short-term response to the demands of the workplace, long-term exposure can lead to chronic psychological problems, including depression symptoms [23]. Depression symptoms may profoundly alter the way individuals perceive and interact with their environment [24] and are likely to be further affected by the advent of automation and advanced production technologies in the workplace [10,28]. As such technologies can increase feelings of alienation and job insecurity, reduce opportunities for meaningful interpersonal interactions, and impose rapid adaptation to constantly evolving systems. Consequently, these factors may amplify the sense of disconnection, stress and anxiety symptoms, highlighting the need for supportive interventions that consider the psychosocial impact of technological change [29]. It is important to underline that depression and anxiety are both common mental health conditions, yet they present with distinct symptom profiles. Anxiety is specifically characterized by excessive worry, fear, and heightened physiological arousal, such as restlessness, rapid heartbeat, and hypervigilance [30]. Depression manifests as persistent and frequent sadness, loss of interest or pleasure in activities, fatigue, and feelings of worthlessness or hopelessness [31]. While these symptoms differ in their core expressions, they can be interconnected with individuals. Interestingly, to the best of our knowledge, depression symptoms that might arise in operators when interacting with advanced production technologies have not been overlooked in previous and current literature. Anxiety symptoms, on the other hand, although closely related to depression and stress symptoms, manifest differently, and require independent consideration in both studies and interventions. Anxiety symptoms are often interpreted as being a by-product of the rapid change of advanced production technologies and the resulting demands in work environments, e.g., high-intensity pace and constant need for digital skill updates [32]. Notably, anxiety symptoms may further burden the individual's cognitive load, thereby creating a situation of overload. This is especially the case with the anxiety symptoms triggered by the advent of advanced production systems, and altogether they can substantially impair pivotal skills, such as decision making and problem solving [32]. In this regard, a recent study found that high levels of fluency, which are related to the well-synchronized interplay between the human and the robot actions, are positively related to long-term teamwork, increased perception of one's mental contribution, and higher trust in the robot [7,10,32]. Conversely, negative attitudes and emotional responses towards robots may play a significant role in the development or increase of psychological distress. Additionally, the relationship between these negative perceptions and psychological symptoms remains underexplored in the existing literature, underscoring the necessity for more comprehensive research in this domain. Mindful of the above, it is imperative to thoroughly investigate these above-mentioned psychological symptoms to better identify both protection and risk factors and to design purposeful intervention strategies for preventing and supporting operators' subjective well-being and organizational effectiveness[1]. In this regard, most of the studies investigating HRI, especially those conducted in the field, have relied on quantitative self-reported instruments only, thereby highlighting the need to widen the methodological approach [8]. The few works investigating HRC using interviews provided rich descriptions of how the work environment, the tasks, and the social dynamics changed after the introduction, for instance, of a collaborative robot (cobot) on the shop floor [33,34], yet they underlooked the operators' psychological state. Cobots are a peculiar type of advanced automation, as they are a form of robotic automation developed to work safely alongside human workers in a shared and collaborative workspace [37], thus highlighting the importance of a mutually supportive interaction in which each party complements the capabilities of the other. Humans provide strategic thinking, creativity, and adaptability, while cobots provide precision, consistency, and resilience. This unique type of collaboration can either yield effective and productive teamwork or it can jeopardize the operators' subjective well-being, depending on the countless factors involved. As a result, the need for an in-depth multifaceted investigation of the human-cobot dyad is timely.

## Objective

The overall aim of this study is to improve the understanding of the subjective well-being of operators in interaction with various advanced production technologies (e.g., cobots, machine vision, pick-to-light), and with a special emphasis on cobots, by subsequently formulating a consensus report aimed at improving workplace conditions. This consensus report will not only provide actionable guidance to enhance workplace policies and training programs but also serve as a foundational tool to promote sustainable and human-focused work environments, in line with Industry 5.0 principles.

We thus move away from a merely technology-oriented standpoint to a more holistic view that places operators, their subjective well-being, and their experiential interactions with advanced production technologies at the centre. Therefore, in line with the principles of Industry 5.0, our investigation is grounded in a human-centric approach. Further enriching the depth of our study, we draw from both the fields of clinical and organizational psychology, emphasizing the importance of considering the operators' perspective and their subjective well-being, by adopting an interdisciplinary approach. More specifically, the purpose of the current study is twofold. First, and more broadly, we aim to explore through the administration of self-report questionnaires the multiple mediating roles of fluency (human-oriented fluency, robot-oriented fluency, and team-oriented fluency) and the negative attitudes toward these technologies. Together, these mediators represent mechanisms through which cognitive well-being dimensions, as the independent variables, (i.e., satisfaction with life, job and career satisfaction, and home-work interface-WRQoL dimensions) influence affective well-being outcomes, as the dependent variables, (i.e., stress, anxiety and depression symptoms) in the context of advanced production technologies (see Table 1).

This objective is based on two hypotheses:

[1] Organizational effectiveness can be defined as the extent to which stakeholders' goals—such as those of investors, employees, and the community—are achieved (Sharma et al., 2019). It is enhanced when employees engage in behaviors that extend beyond their formal roles, commonly referred to as organizational citizenship behaviors. These behaviors are more likely to be exhibited by employees who experience high levels of job satisfaction [35,36].

1. Higher levels of fluency (human-oriented, robot-oriented, and team-oriented) are hypothesized to positively and partially mediate the relationship between cognitive and affective well-being. Fluency is expected to act as a protective factor, facilitating smoother interactions with advanced production technologies and thereby reducing psychological distress (i.e., anxiety, stress, and depression symptoms). As a mediating mechanism, fluency indirectly alleviates psychological distress by lowering cognitive workload and minimizing task-related frustrations inherent in complex HRI [38,39]. Partial mediation is proposed since evidence from human-technology interaction research indicates that while fluency reduces emotional strain, it cannot fully eliminate all sources of psychological distress [39]. For example, even operators with high levels of fluency may experience stress symptoms due to external factors, such as organizational change, time pressures, or conflicting demands, which directly have an impact on affective well-being [40].
2. Negative attitudes toward advanced production technologies (both emotional and social influence dimensions) will negatively and fully mediate the relationship between cognitive and affective well-being. Full mediation is hypothesized as these negative attitudes include the main psychological and social barriers that operators can experience when interacting with advanced production technologies. This assumption is based on prior studies that observed that negative attitudes capture the emotional and social mechanisms that diminish well-being in technology-intense environments [41,42].

Second, using semi-structured audio-recorded interviews, we aim to conduct an in-depth qualitative analysis of operators' perceptions of their subjective well-being and lived experiences within the context of HRI and HRC, focusing specifically on the interaction with cobots and also considering the co-workers' social relationships. For the extraction and understanding of pivotal textual data, we will employ advanced text-mining methodologies [43].

At the conclusion of the data collection and analysis, should specific areas of difficulties emerge, an optional psychoeducational intervention will be proposed to the organization. Such focus groups will aim to provide operators with practical tools to enhance their subjective well-being.

To our knowledge, this is the first cross-sectional study to comprehensively examine the relationship between the variables outlined above and operators using, interacting, and collaborating with advanced production technologies within manufacturing companies.

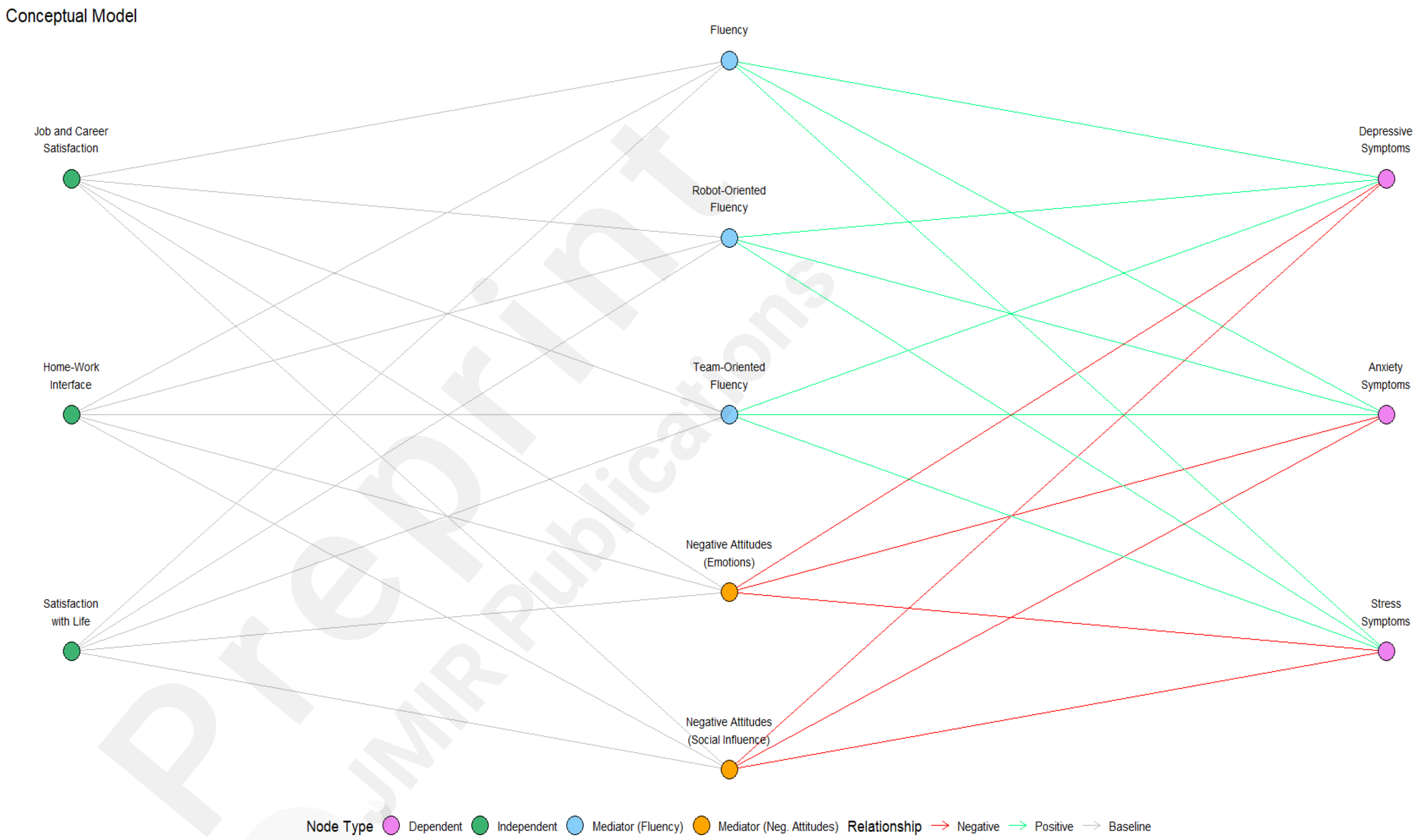
**Table 1.** Summary of the constructs investigated through the specific mean.

| Constructs | | Definition | Investigated with | |
|---|---|---|---|---|
| | | | Questionnaire | Semi-structured interviews |
| **Affective well-being** | *Depression symptoms* | ● Feelings of persistent and frequent sadness, loss of interest or pleasure in activities, fatigue, and feelings of worthlessness or hopelessness.<br>● It can also involve physical and cognitive symptoms, such as changes in appetite, sleep disturbances, fatigue and difficulty in concentrating. | x | |
| | *Anxiety symptoms* | ● Excessive worry, fear, and heightened physiological arousal, such as restlessness, rapid heartbeat, and hypervigilance. | x | |
| | *Stress symptoms* | ● Stress is a physiological or psychological response to internal or external stressors.<br>● Stress symptoms are a human response to cope with life's challenges and threats.<br>● The presence of long-term stress symptoms and the way they are coped with can have a negative impact on subjective well-being, | x | |

| | | | | |
|---|---|---|---|---|
| | | which can in turn impact on the organizational one. | | |
| **Cognitive well-being** | *Home-work interface* | ● The balance and harmony between home and work life. | x | |
| | *Job (and career) satisfaction* | ● The positive attitude individuals have regarding their job and career advancement. | x | x |
| | *Satisfaction with life* | ● Life satisfaction is related to the assessment of individuals' quality of life. | x | |
| **Human factors** | *Physical and mental workload* | ● The physical workload is the physical effort required by an operator in a manufacturing company.<br>● With the integration of robots and particularly cobots, the physical workload can be modified.<br>● Mental workload refers to the cognitive and psychological demands placed on an operator. | | x |
| | *Team-oriented fluency in human-robot collaboration* | ● Well-synchronized interplay of human and robot actions. | x | x |
| | *Negative attitudes and emotions toward robots* | ● Individuals' attitudes and emotions when interacting with robots of different types. | x | |

| | | | | |
|---|---|---|---|---|
| | *Trust* | ● The dispositional attitude that a robot will support the achievement of the individual's goals in a situation characterized by uncertainty and vulnerability. | | x |
| | *Acceptance* | ● The beliefs that robots will be helpful for the individuals' work and that it will not threaten their role in the workforce community. | | x |
| | *Usability* | ● The extent to which working with the robot is effective, reasonably effortless and satisfactory. | | x |
| | *Introduction of the robot/cobot and training* | ● The modality adopted by the organization to introduce the robot and particularly the cobot in the production line and the provision of training. | | x |
| | *Perceived risks and benefits* | ● Exploration of which changes are deemed beneficial, and which are perceived as a threat in HRI and HRC domains. | | x |
| | *Social relationships among co-workers* | ● The extent to which the introduction of the robot and particularly the cobot has changed the social dynamics among co-workers. | | x |

**Figure 1.** The conceptual model of a path analysis investigating the role of fluency in HRI and negative attitudes towards advanced production technologies between cognitive and affective well-being



## Ethical approval and consent to participate

The study has been approved by the Ethical Committee of Human-Inspired Technologies of the University of Padova (Italy), with the protocol number (2023_212R1). Moreover, all participants will be asked to read carefully an information sheet describing all the research details, and to sign informed consent before taking part in the study. At least one researcher will be present to answer all their answers and doubts.

## Design

Following the call made by Meissner and colleagues [8], this cross-sectional study will implement a mixed-method approach, incorporating both quantitative and qualitative data collection techniques. Both the quantitative and qualitative parts of the study have been conceived to be intimately related, yet independent. Participation in the semi-structured interviews is voluntary, and as such, it is possible that some operators who complete the survey may choose not to participate in the interviews, ensuring flexibility. The semi-structured interviews are designed to focus specifically on the operator's interaction with advanced production technologies, such as cobots, providing an opportunity for participants to share experiences that may not be fully captured in their survey responses.

More specifically, as regards the *quantitative section*, a digital survey containing the self-report questionnaires will be administered, relying on an online platform, namely Qualtrics. The duration of the digital survey will be approximately 20 minutes. Before filling in the questionnaire, the operators should read the study information and sign informed consent to participate in the study. The digital survey will start by asking (i) socio-demographic questions, such as age, sex, nationality, educational level, marital status, and presence/absence of offspring. Subsequently, (ii) questions regarding the company in which the operators work will solicit information on their role, tenure, work shifts, and the specific advanced production technologies they engage with, as well as their tasks (i.e., picking, packing, palletizing, welding, assembling items, handling, inspecting products for quality, disassembly, holding heavy weight, transporting goods, and other). Additionally, if operators reported working with cobots, a question regarding the degrees of such collaboration (i.e., independent, simultaneous, sequential, supportive) will be proposed [44,45]. Operators should then complete (iii) a brief battery of standardized self-report questionnaires designed to assess their satisfaction with life, WRQoL dimensions (i.e., job and career satisfaction, and home-work interface), their potential for psychological distress (i.e., depression, anxiety, and stress symptoms), the negative attitudes toward advanced production technologies, and fluency in HRI.

The *qualitative section* will employ semi-structured audio-recorded interviews designed to last approximately 60 minutes. These semi-structured interviews have the purpose of exploring the operators' perceptions and lived experiences with advanced production technologies. In particular, the themes addressed will cover 9 dimensions related to the operators' subjective well-being in using and interacting with advanced production technologies (i.e., the introduction of them and training, human factors, physical and cognitive workload, trust, acceptance and usability, capabilities of technologies, potential risks and benefits, and interpersonal relationships among co-workers).

At the end of the data collection, psychoeducational interventions will be implemented through the means of the focus groups. Specifically, based on questionnaire outcomes related to cognitive and affective well-being, psychoeducational focus groups will be proposed to the company, and operators will be invited to participate voluntarily. Each focus group will be carried out separately for each participating company, highlighting the unique organizational and contextual factors affecting operators within their specific workplace. The intervention will be moderated by two psychologists (a clinical and an organizational psychologist), by addressing the potential psychological distress of operators. The focus groups are designed as part of the intervention strategy. While the qualitative section primarily aims to gather in-depth insights into operators' lived experiences and perceptions through semi-structured interviews, the focus groups serve a distinct purpose. They intend to provide psychoeducational support, by potentially improving their overall well-being.

## Funding

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## Study Population and recruitment

We will recruit operators working in different manufacturing companies located in the North-East of Italy, particularly those dealing with advanced production technologies.

To determine the necessary sample size required for pursuing the objective related to the quantitative section, a power analysis was conducted, using the semPower library [46] under the RStudio environment, assuming a Root Mean Square Error of Approximation (RMSEA) effect cut-off equal to 0.10, a p-value of 0.05, a power of 0.80, and df = 52. The computation resulted in a minimum number of 60 participants.

Notwithstanding this outcome, we acknowledge that the estimated sample size represents the minimum threshold required for adequate statistical power, particularly in models with multiple mediators and paths. Therefore, we aim to exceed the minimum threshold by expanding recruitment efforts across participating companies.

### Inclusion and exclusion criteria

Given the purpose of the study, specific inclusion and exclusion criteria have been delineated. The criteria for participation are outlined as follows: (i) prospective participants should fall within the age range of 18 to 65 years, ensuring that the sample represents the working-age population within the manufacturing company, (ii) being employed as shop floor operators or in a manufacturing company that has introduced advanced production technologies, thereby having first-hand experience with such technologies, (iii) manufacturing companies in which advanced production technologies, such as cobots, pick-to-light systems, and machine vision technologies, have been introduced within the last 5 years. This criterion ensures that the study focuses on operators interacting with relatively recent implementations of advanced production technologies, reflecting the evolving practices of Industry 5.0. Moreover, (iv) the adoption of cobots within the company to administer the semi-structured interview protocol, and, lastly, (v) willingness to participate and provide informed consent. Participants will be excluded whether: (i) not directly engaged in the use of advanced production technologies or cobots, and (ii) diagnosed with cognitive impairments or any other conditions that might hinder their ability to understand, engage in, or provide feedback.

## Quantitative data collection: self-reported questionnaires

All the self-report questionnaires are validated in [*blank for review purposes*] for adults' respondents, except for the fluency in human-robot interaction scale [9], for which we carried out a back-translation procedure. Moreover, all the below-mentioned instruments have demonstrated good psychometric properties.

**Depression symptoms.** Depression symptoms will be measured through the Patient Health Questionnaire-9 [47], which is a brief self-reported unidimensional instrument that incorporates the Diagnostic and Statistical Manual of Mental Disorders, fourth edition, text revision (DSM-IV-TR) [48]. The questionnaire was developed to assess and monitor the severity of depression symptoms in the previous 2 weeks through 9 items rated on a 4-point Likert scale, from 0 ("never") to 3 ("almost every day"). A threshold score of 10 is indicative of clinically significant depression symptoms (scores 0-27). The PHQ-9 stratifies depression severity into five severity categories: absent, subthreshold depression symptoms, mild depression symptoms, moderate depression symptoms, and major depression symptoms. Assessing depression symptoms, e.g., persistent and frequent feelings of sadness, guilt and worthlessness, is relevant as depression is often considered a proxy of the individual's mental health [17]. Moreover, depression symptoms can alter how the individual perceives events, and they can result in a long-term exposure to stress symptoms [23,27].

**Anxiety symptoms.** Anxiety symptoms will be evaluated using the Generalized Anxiety Disorder-7 (GAD) scale [49], which is a brief self-reported unidimensional measure aimed at screening probable cases of GAD and assessing the symptoms' severity in the previous 2 weeks. The GAD-7 comprises 7 items based on a 4-point Likert scale, from 0 ("never") to 3 ("almost every day"). A score equal to 10 indicates relevant anxiety symptoms (score ranging between 0 and 21). The questionnaire included three categories of severity according to the DSM-IV-TR criteria: mild anxiety symptoms, moderate anxiety symptoms, and severe anxiety symptoms. The investigation of anxiety symptoms is motivated by the fact that they may be caused by the rapid change in production technologies and the consequent new demands in one's job, leading to significant psychological distress [10].

**Satisfaction With Life.** Satisfaction with life scale (SWLS) [50] will be administered to assess operators' global cognitive perception of one's life satisfaction. The SWLS is a 5-item self-report unidimensional questionnaire based on a 7-point Likert scale, from 1 ("strongly disagree") to 7 ("strongly disagree"). Assessing the overall level of life satisfaction is relevant in this context because higher levels of life satisfaction are linked to better job performance [51]. Additionally, it was found that work-related events impact one's level of satisfaction with life [52].

**Work-related quality of life**. Work-related quality of life (WRQoL)[2] [18] will be assessed through the Work-related quality of life scale. The WRQoL is a multidimensional instrument characterized by 25 items plus an extra item—which investigates the overall level of WRQoL—rated on a 5-point Likert scale, from 1 ("strongly disagree") to 5 ("strongly agree"). These items are divided into 7 factors (i.e., control at work, home-work interface, job and career satisfaction, working conditions, employee engagement, and stress at work). In line with the purpose of the present study, we will focus on the home-work interface, job and career satisfaction, and stress at work, further including the extra item to reflect an overall level of operators' WRQoL. The choice to focus only on specific subscales is motivated by the role that those constructs play on the individual's well-being. Indeed, advanced production technologies are known to foster unlimited connection, thereby threatening the separation between work and personal domains [53]. Specifically referring to human-cobot interaction, poor synchronization in the actions of human and robotic agents is related to lower levels of job satisfaction [54]. Finally, the introduction of new industrial systems, such as cobots, and the conversion of the workers' role from operator to supervisor has brought to a significant increase in their stress levels, which can negatively impact different human functions [23].

**Fluency in HRI**. The quality of human-robot interaction (HRI) will be evaluated using the Fluency in Human-Robot Interaction Scale (FHRIS) [9]. The FHRIS is a multidimensional instrument characterized by 6 items rated on a 7-point Likert scale, from 1 ("strongly disagree") to 7 ("strongly agree"). The scale is composed of 3 factors, namely human-oriented fluency, which evaluates the worker's emotional states experienced during the HRI, robot-oriented fluency assesses the perception of the robot's contribution during the collaboration, and team-oriented fluency refers to the team's harmony. Including the assessment of fluency is grounded by the fact that a well-coordinated meshing of human and robots' actions was found to positively influence long-term teamwork, increase the perception of one's mental contribution and foster higher levels of trust in the robot [9,55].

[2] This instrument presents the advantage, compared to other measures, of allowing researchers, organizational and clinical professionals to assess WRQoL in both organizational and clinical settings [18].

**Negative attitudes toward advanced production technologies.** The negative attitudes toward advanced production technologies will be assessed using the Negative Attitude toward Robots Scale (NARS) [56]. The NARS is a multidimensional instrument designed to evaluate the negative attitudes that workers can experience in their interaction with robots. The NARS is composed of 17 items rated on a 5-point Likert scale ranging from 1 (“strongly disagree”) to 5 (“strongly agree”), encompassing three scales, (i) negative attitudes toward situations of interaction with robots, (ii) negative attitudes toward the social influence of robots, and (iii) negative attitudes toward emotions in interaction with robots. The inclusion of only these latter two subscales was driven by the need to align with the research objectives while ensuring a streamlined and efficient questionnaire completion process for respondents. Moreover, attitudes towards robots is worthy of investigation because it is affected by several factors, including expertise in the job, and it is also related to the level of trust in the robotic system [57,58].

**Qualitative data collection: audio-recorded semi-structured interviews**

A semi-structured interview protocol, called Exploration of Psychological Impacts in Collaborative Operator Settings (EPICOS) [59], combines open-ended questions with dichotomous and multiple-choice scales, creating a holistic understanding of the dynamics related to the HRI and HRC. Through EPICOS, our aim is to highlight 9 key dimensions related to operators’ subjective well-being when using, interacting, and collaborating with robots and particularly with cobots in the context of manufacturing 5.0. In particular, the 9 areas comprise several open-ended, dichotomous responses, and Likert scale questions. The 9 areas that will be analyzed along with their summarized questions are reported below.

- *Introduction of advanced production technologies and their training*: this area of investigation refers to the modalities with which the introduction of advanced production technology, especially cobots, is communicated to employees and the training they receive, which significantly contributes to how workers receive and interact with them [60].
- *Human factors, including physical ergonomics, tasks, and degree of HRC*: questions in this area explore how operators and advanced production technologies interact in Industry 5.0, and the organizational and clinical implications that their interaction has for the subjective well-being of the operators. It is well-known that the characteristics of the task allocation, the speed and trajectory of the robotic arm significantly impact on the worker’s cognitive and affective state [14,54].
- *Trust*: this area investigates the workers’ attitudes and beliefs that the technological agent will help in accomplishing the task. The level of trust in robots is key to ensure successful HRI cooperation and it also influences the use that workers make of technology [7,14].
- *Usability and acceptance*: these questions refer to factors related to the ease of interacting with the robot, and particularly with the cobot, and the extent to which workers show a genuine willingness to work with it. These aspects are relevant as poor usability hinders a smooth and satisfactory usage of the technology, while

low levels of acceptance hamper the very use and adoption of the technology itself [61].

- *Perceived risks and benefits*: this area refers to the potential threats that workers associate with technology and the envisioned or experienced advantages related to it. More specifically, this area will encompass both the risks and benefits pertaining to physical interaction with technology, e.g., safety issues, the wider perspective, and the role replacement. Attributing a certain level of risk to technology can negatively affect the acceptance of the technology itself [6].
- *Interpersonal relationships among co-workers*: this area of investigation is meant to explore whether and how the presence of advanced production technology has changed the relationships among workers. This area of investigation is relevant because social relationships at work significantly impact individuals' well-being [8,62].

### Statistical Analysis

Statistical analyses will be conducted using R custom code through the RStudio environment.

Descriptive statistics for both discrete (e.g., frequencies) and continuous variables (e.g., mean, standard deviation) will be run.

Bivariate Pearson's *r* correlation coefficient will be deployed for evaluating the association between age, cognitive well-being (i.e., job and career satisfaction, home-work interface-WRQoL, and satisfaction with life), affective well-being (i.e., anxiety, depression, and stress symptoms), negative attitudes toward advanced production technologies, and fluency in HRI ($P < 0.05$). According to Cohen's guidelines [63], correlation coefficients ranging between 0.10 and 0.29 indicate a "small effect size", between 0.30 and 0.49 represent a "medium effect size", and above 0.50 represent a "large effect size".

A path analysis will be carried out to explore the direct and indirect associations between operators' cognitive well-being (i.e., WRQoL dimensions and satisfaction with life) as independent variables, and affective well-being (i.e., depression, anxiety, and stress symptoms) as the dependent variables. Central to this analysis is the investigation of the multiple mediating roles of fluency in HRI and the negative attitudes and emotions toward advanced production technologies, by highlighting the indirect effect pathways between the above-mentioned variables. The strength and direction of these associations will be quantified using standardized regression coefficients (β) and the robustness of these estimates will be reported through confidence intervals (CI).
A thematic analysis will be undertaken, by relying on the text-mining technique, using the Quanteda package [64], to capture textual data within interview transcripts, thus highlighting emergent patterns and themes. The analysis will be carried out on the verbatim transcripts of the semi-structured interviews by turning any numbers into letters and removing punctuation and stopwords. Subsequently, all semi-structured

interviews will be analyzed to explore the most frequent co-occurrences and digrams, based on a rule-of-thumb, in which words that will be repeated a minimum of three times will be considered co-occurrences as well as for digrams. The findings from this analysis will be cross-referenced with the quantitative results to ensure consistency and to identify areas of alignment or divergence. For example, themes related to fluency and their perceived impact on stress reduction, as identified through text-mining, will be compared with the statistical relationships observed in the path analysis. The text-mining process itself will undergo validation through iterative refinement of algorithms and checks for coherence and relevance, ensuring that semantic clusters correspond to meaningful constructs within the study's context. This triangulation between quantitative and qualitative findings will deepen the understanding of the factors influencing operators' well-being in HRI.

## Discussion

Previous research has already addressed many aspects of the relationship between operators and advanced production technologies, mainly focusing on job performance or work-related stress symptoms using either quantitative or qualitative methods alone. However, how the interaction between operators and advanced production technologies impacts individual subjective well-being has been neglected so far. Still, the changes in production tasks driven by technological innovation have been shown to exert negative effects on operators' well-being [17,28]. These effects, often manifesting as increased cognitive workload, anxiety, and stress symptoms, require deeper examination [23,28,65]. Indeed, if these symptoms are not proactively addressed and prevented, they may develop into severe psychological distress, which can emerge in various forms, such as increased anxiety, and/or depression. Over time, these symptoms can significantly impair an individual's daily functioning, affecting their ability to work and maintain healthy interpersonal relationships. In the present cross-sectional study, we aim to address this gap by integrating quantitative and qualitative data in order to better comprehend the role played by several relevant factors, namely fluency in HRI and the dispositional negative attitudes toward advanced production technologies, to further promote operators' subjective well-being. In this regard, from a quantitative point of view, we expect that the quality of the interaction between operators and the advanced production technologies, namely fluency in HRI, may act as a protective factor against the development or worsening of operators' psychological distress. Additionally, satisfaction with life, career and job satisfaction as well as the home-work interface may function as independent variables that directly contribute to operators' psychological well-being. Higher job satisfaction fosters a sense of accomplishment and professional stability, reducing vulnerability to depression, anxiety, and stress symptoms [22]. Likewise, a positive home-work balance enhances the ability to manage both personal and professional responsibilities effectively, mitigating psychological distress [21]. Moreover, satisfaction with life reflects a broader sense of contentment and well-being that buffers individuals against the cumulative effects of the workplace and life stressors [67]. Together, these variables, in conjunction with HRI fluency—human-oriented, robot-oriented, and team-oriented—can have a positive impact on the psychological outcomes, highlighting their critical role in shaping a healthier and more sustainable working environment. Conversely, negative attitudes towards these advanced production technologies may be conceived as risk factors that could contribute to the onset of psychological distress, given the scarcity of the scientific literature, we expect to explore respondents' lived experiences and interpret them referring to the scores at the questionnaires, thereby building a comprehensive overview of the subjective well-being of the operator who uses, interacts and collaborates with cobots. By qualitatively delving into the workers' self-reported experiences and feelings, it will also be possible to explore aspects related to their reception of the novel technology introduced, thereby unveiling possible additional distress factors, e.g., fear of job loss, echoing previous research [67]. In this regard, as part of the study, psychoeducational interventions will be proposed to address organizational-specific challenges and psychological stressors, providing operators with practical strategies to address workplace challenges and fostering a supportive organizational environment. This aligns with the principles of Industry 5.0 by placing operators' well-being and workplace challenges at the centre of interventions aimed at fostering sustainable HRI and HRC.

This multi-method approach adopted in this study offers significant value by combining the strengths of both quantitative and qualitative data collection techniques. While the quantitative data provides a structured and systematic analysis of the relationships between cognitive well-being, affective well-being, and mediating factors, such as fluency in HRI and negative attitudes toward advanced production technologies, the qualitative interviews offer an opportunity to explore these phenomena in greater depth. After the quantitative data collection, the interviews enable the collection of operators' lived experiences and the contextualization of the findings from the self-reported questionnaires. This sequential approach allows the application of the quantitative results to inform the focus of the interviews, thereby ensuring that the qualitative data collection is targeted. The interviews also provide nuanced insights into the subjective perspectives of operators, capturing details that are often difficult to quantify, such as their perceptions of collaboration with technologies, the organizational challenges they face, and the interpersonal and social dynamics within their workplaces. These insights complement the quantitative findings by highlighting the mechanisms through which fluency, and attitudes toward advanced production technologies influence subjective well-being outcomes, as well as identifying potential areas for support that may not emerge from survey data alone. This integration of methods is particularly important in the context of Industry 5.0, where a human-centric approach reflects a comprehensive understanding of operators' experiences to design interventions that promote well-being. The integration and triangulation of quantitative and qualitative findings, also through the use of the text mining technique, enhances the study's methodological robustness. Addressing these issues is crucial not only for the well-being of individual operators but also for the overall health of the organization. Therefore, proactive measures in this regard will benefit both individual operators and the organization as a whole, leading to a more sustainable and productive work environment. Indeed, by fostering a work environment that addresses subjective well-being [68], intended as affective (i.e., depression, anxiety, and stress symptoms) and cognitive well-being (i.e., satisfaction with life and WRQoL) of operators, organizations can create a more resilient, engaged, and ultimately effective workforce capable of proactively adapting to the evolving demands of the modern industrial age. This conceptualization is in fact based on the three founding pillars of Industry 5.0 (i.e., human-centered, sustainability, and resilience), recognizing that the psychological well-being of operators is an integral part of sustainable productivity.

Still, we acknowledge some limitations of the present study. Firstly, it was designed to be cross-sectional, thus failing to capture the interaction between operators and advanced production technologies over time. While a longitudinal design would provide a more in-depth understanding of the temporal dynamics and causal relationships between cognitive and affective well-being, fluency in HRI, and negative attitudes toward advanced production technologies, this study adopts a cross-sectional design for several practical and methodological reasons. Conducting research across multiple manufacturing companies presents logistical challenges, particularly in ensuring consistent participation over time and varied work schedules typical of industrial environments [69]. Furthermore, as an exploratory study addressing a gap in the literature, a cross-sectional design enables the establishment of baseline relationships and the potential identification of key mediating factors, laying the groundwork for future research. Secondly, the sample is drawn exclusively from manufacturing companies located in North-East Italy. While this region is a hub for industrial innovation and advanced production technology adoption, the findings may not be directly generalized to other geographical areas or industrial sectors. Differences in cultural, organizational, and technological contexts may influence the applicability of the results. Future research should expand to include diverse geographical locations and industries to validate and extend the findings that will emerge from this study. Moreover, the organizational level and all the related aspects (e.g., organizational culture), which may play an important role, were not considered, as the study is narrowly focused on the individual and subjective level. Additionally, aspects such as the fear of job loss, which may affect the worker's subjective well-being, are not measured quantitatively. While this construct is explored with the interview, including a quantitative assessment may add a further layer to the model, thereby leading to a more thorough understanding of the worker's subjective well-being. Finally, despite reasoning within the paradigm of Industry 5.0, especially emphasizing the need to bring operators to the forefront, social inclusiveness, which may be involved in their well-being, was not considered. Notwithstanding this, the investigation of the relationship between all the above-mentioned variables will provide a comprehensive view of the factors that contribute to operators' subjective well-being in HRI and HRC in manufacturing 5.0. This understanding will allow us to achieve the final goal of developing a consensus report that will provide guidance to companies that have adopted advanced production technologies, further considering the importance of the interaction between operators and cobots, to improve workplace conditions both organizationally and clinically, as well as to identify adaptive organizational and clinical strategies to support operators' well-being and optimize HRI. The consensus report will also serve as a practical framework for guiding workplace policies, such as implementing measures to foster subjective well-being and effective HRI, while addressing job satisfaction. Additionally, it will inform the development of tailored training programs for operators, ensuring they are equipped with the necessary skills to adapt to evolving technologies while maintaining a healthy work-life balance. These practical implications highlight the report’s potential to create more sustainable and operator-focused workplaces, in line with Industry 5.0 principles. Recognition and early intervention are crucial to reduce any potential psychological distress and thus promote operators’ mental well-being. Indeed, through the identification of key variables that can influence the operators’ subjective well-being, organizations can tailor specific psycho-educational interventions, training toward the use, interaction, and collaboration with these advanced production technologies, such as cobots, as well as awareness campaigns or workshops. This approach can improve the quality of HRI and HRC, by ameliorating the overall operators-advanced production technologies dynamics, promoting subjective well-being, and diminishing potential mental health difficulties. As noted by Ghisleri and colleagues [70], the role of work in one’s life is pivotal, because it does not only respond to instrumental needs, rather it also answers to crucial intrinsic needs of maintaining self-esteem and satisfactory social relations. Therefore, investigating whether and how new technological working tools can be effectively integrated not only in the work practices but also in the workers’ psychosocial workspace is crucial to ensure both the workers’ psychological fit and the organization performance. The present study is not a mere statistical exploration, it aims to be an essential tool to understand and guide the complexities of contemporary workplaces, where humans and robots coexist and should coexist harmoniously.

## Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Abbreviations

EPICOS: Exploration of Psychological Impacts in Collaborative Operator Settings

FHRIS: Fluency in Human-Robot Interaction Scale

GAD: Generalized Anxiety Disorder

HRI: Human-Robot Interaction

HRC: Human-Robot Collaboration

IoT: Internet of Things

NARS: Negative Attitude toward Robots Scale

PHQ-9: Patient Health Questionnaire-9

SWL: Satisfaction With Life

WRQoL: Work-related Quality of Life

## Authors' contributions

Conceptualization: all authors; Methodology: B. G. & O. V.; Formal analysis: B. G., & O. V.; Investigation: B. G., & O. V.; Writing - Original Draft: B. G., & O. V.; Writing - Review & Editing: all authors; Visualization: B. G.; Supervision: G. L. & S. S.

### Data Availability Statement

This manuscript describes a protocol study and, as such, does not include any primary data.

## References


1. Kagermann H, Wahlster W, Helbig J. Recommendations for implementing the strategic initiative Industrie 4.0, securing the future of German manufacturing industry. Final report of the Industrie 4.0 Working Group; 2013. Available from: https://www.din.de/resource/blob/76902/e8cac883f42bf28536e7e8165993f1fd/recommendations-for-implementing-industry-4-0-data.pdf
2. Kumar R, Gupta P, Singh S, Jain D. Human empowerment by Industry 5.0 in digital era: analysis of enablers. In: Advances in industrial and production engineering: select proceedings of FLAME. Singapore: Springer; 2020. p. 401-410.
3. Neumann WP, Winkelhaus S, Grosse EH, Glock CH. Industry 4.0 and the human factor: a systems framework and analysis methodology for successful development. Int J Prod Econ. 2021;233:107992. doi:10.1016/j.ijpe.2020.107992.
4. Nahavandi S. Industry 5.0: a human-centric solution. Sustainability. 2019;11(16):4371. doi:10.3390/su11164371.
5. European Union. Digital technologies, work and psychosocial risks: evidence and implications for occupational safety and health. 2022. Available from: https://osha.europa.eu/en/publications/digital-technologies-work-and-psychosocial-risks-evidence-and-implications-occupational-safety-and-health.
6. Jacob F, Grosse EH, Morana S, König CJ. Picking with a robot colleague: a systematic literature review and evaluation of technology acceptance in human–robot collaborative warehouses. Comput Ind Eng. 2023;109262. doi:10.1016/j.cie.2023.109262.
7. Sanders T, Kaplan A, Koch R, Schwartz M, Hancock PA. The relationship between trust and use choice in human-robot interaction. Hum Factors. 2019;61(4):614-626. doi:10.1177/0018720818799712.
8. Meissner A, Trübswetter A, Conti-Kufner AS, Schmidtler J. Friend or foe? Understanding assembly workers' acceptance of human-robot collaboration. ACM Trans Hum Robot Interact. 2020;10(1):1-30. doi:10.1145/3368900.
9. Paliga M, Pollak A. Development and validation of the fluency in human-robot interaction scale: a two-wave study on three perspectives of fluency. Int J Hum Comput Stud. 2021;155:102698. doi:10.1016/j.ijhcs.2021.102698.
10. Teepe GW, Glase EM, Reips UD. Increasing digitalization is associated with anxiety and depression: a Google Ngram analysis. PLoS One. 2023;18(4). doi:10.1371/journal.pone.0284091.
11. Granulo A, Fuchs C, Puntoni S. Psychological reactions to human versus robotic job replacement. Nat Hum Behav. 2019;3(10):1062-1069.
12. Kaur G, Banerjee S, Banerjee NK. Studying worker perceptions on safety, autonomy, and job security in human-robot collaboration. In: Proceedings of the 9th International Conference on Automation, Robotics and Applications (ICARA). 2023; Abu Dhabi, United Arab Emirates. p. 187-191. doi:10.1109/ICARA56516.2023.10125842.
13. Orso V, Bassi G, Salcuni S, Gamberini L. From human-cobot interaction to human-cobot workteam: a mixed-method psychosocial approach. In: Proceedings of the 1st International Workshop on Worker Related Relationships - Exploring

Transdisciplinary Perspectives on Robotic Futures; 2024 Mar 11.
14. Kopp T, Baumgartner M, Kinkel S. How linguistic framing affects factory workers' initial trust in collaborative robots: the interplay between anthropomorphism and technological replacement. Int J Hum Comput Stud. 2022;158:102730. doi:10.1016/j.ijhcs.2022.102730.
15. Pagán-Castaño E, Maseda-Moreno A, Santos-Rojo C. Wellbeing in work environments. J Bus Res. 2020;115:469-474. doi:10.1016/j.jbusres.2019.03.021.
16. Storm FA, Chiappini M, Dei C, Piazza C, André E, Reißner N, et al. Physical and mental well-being of cobot workers: a scoping review using the Software-Hardware-Environment-Liveware-Liveware-Organization model. Hum Factors Ergon Manuf. 2022;32(5):419-435. doi:10.1002/hfm.20932.
17. Wei W, Li L. The impact of artificial intelligence on the mental health of manufacturing workers: the mediating role of overtime work and the work environment. Front Public Health. 2022;10:862407. doi:10.3389/fpubh.2022.862407.
18. Garzaro G, Clari M, Donato F, Dimonte V, Mucci N, Easton S, et al. A contribution to the validation of the Italian version of the work-related quality of life scale. Med Lav. 2020;111(1):32-45. doi:10.23749/mdl.v111i1.8570.
19. Bataineh KA. Impact of work-life balance, happiness at work, on employee performance. Int Bus Res. 2019;12(2):99-105. doi:10.5539/ibr.v12n2p99.
20. Locke EA. The nature and causes of job satisfaction. In: Dunnette MD, editor. Handbook of industrial and organizational psychology. 1st ed. Chicago, IL: Rand McNally; 1976. p. 1297-1343.
21. Sirgy MJ, Lee DJ. Work-life balance: an integrative review. Appl Res Qual Life. 2018;13:229-254. doi:10.1007/s11482-017-9509-8.
22. Stansfeld SA, Candy B. Psychosocial work environment and mental health: a meta-analytic review. Occup Environ Med. 2006;62(2):105-112. doi:10.1136/oem.2004.01610.
23. Blandino G. How to measure stress in smart and intelligent manufacturing systems: a systematic review. Systems. 2023;11(4):167. doi:10.3390/systems11040167.
24. Kim HD, Park SG, Won Y, Ju H, Jang SW, Choi G, et al. Longitudinal associations between occupational stress and depressive symptoms. Ann Occup Environ Med. 2020;32. doi:10.35371/aoem.2020.32.e29.
25. Bhui K, Dinos S, Galant-Miecznikowska M, de Jongh B, Stansfeld S. Perceptions of work stress causes and effective interventions in employees working in public, private, and non-governmental organisations: a qualitative study. BJPsych Bull. 2016;40(6):318-325. doi:10.1192/pb.bp.115.050823.
26. Ghani B, Memon KR, Han H, Ariza-Montes A, Arjona-Fuentes JM. Work stress, technological changes, and job insecurity in the retail organization context. Front Psychol. 2022;13:918065. doi:10.3389/fpsyg.2022.918065.
27. Gotlib IH, Joormann J. Cognition and depression: current status and future directions. Annu Rev Clin Psychol. 2010;6:285-312. doi:10.1146/annurev.clinpsy.121208.131305.
28. Johnson A, Dey S, Nguyen H, Groth M, Joyce S, Tan L, et al. A review and agenda for examining how technology-driven changes at work will impact

workplace mental health and employee well-being. Aust J Manag. 2020;45(3):402-424. doi:10.1177/0312896220922292.
29. European Agency for Safety and Health at Work. Digital technologies, work and psychosocial risks: evidence and implications for occupational safety and health. 2021. Available from: https://osha.europa.eu/en/publications/digital-technologies-work-and-psychosocial-risks-evidence-and-implications-occupational-safety-and-health.
30. American Psychiatric Association. Diagnostic and statistical manual of mental disorders. 4th ed., text revision; 2000.
31. Beck AT, Steer RA, Brown GK. Manual for the Beck Depression Inventory-II. San Antonio, TX: Psychological Corporation; 1996.
32. Lee JD, See KA. Trust in automation: designing for appropriate reliance. Hum Factors. 2004;46(1):50-80. doi:10.1518/hfes.46.1.50_30392.
33. Hopko S, Wang J, Mehta R. Human factors considerations and metrics in shared space human-robot collaboration: a systematic review. Front Robot AI. 2022;9:799522. doi:10.3389/frobt.2022.799522.
34. Welfare KS, Hallowell MR, Shah JA, Riek LD. Consider the human work experience when integrating robotics in the workplace. In: Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI). 2019. p. 75-84. doi:10.1109/HRI.2019.8673256.
35. Organ DW, Ryan K. A meta-analytic review of attitudinal and dispositional predictors of organizational citizenship behavior. Pers Psychol. 1995;48(4):775-802. doi:10.1111/j.1744-6570.1995.tb01781.x.
36. Serbinenko I, Ludviga I. Organizational citizenship behaviour: evolution of the concept in the scope of Industry 4.0 and Industry 5.0. J Bus Manag. 2023;21:1-21.
37. Karl A, Wisnowski J, Rushing WH. A practical guide to text mining with topic extraction. WIREs Comput Stat. 2015;7(5):326-340. doi:10.1002/wics.1361.
38. Kühl N, Goutier M, Hirt R, Satzger G. Machine learning in artificial intelligence: towards a common understanding. In: Proceedings of the 52nd Hawaii International Conference on System Sciences; 2019. p. 5485-5494.
39. Fischer T. Human-robot interaction in industry: current research and future directions. Trends Cogn Sci. 2020;24(3):157-159. doi:10.1016/j.tics.2020.01.004.
40. Bakker AB, Demerouti E. Job demands-resources theory: taking stock and looking forward. J Occup Health Psychol. 2017;22(3):273-285. doi:10.1037/ocp0000056.
41. Ab Wahab M, Tatoglu E. Chasing productivity demands, worker well-being, and firm performance: the moderating effects of HR support and flexible work arrangements. Pers Rev. 2020;49(4):1056-1078. doi:10.1108/PR-01-2019-0026.
42. Konuk H, Ataman G, Kambur E. The effect of digitalized workplace on employees' psychological well-being: digital Taylorism approach. Technol Soc. 2023;72:102227. doi:10.1016/j.techsoc.2023.102227.
43. Colgate JE, Peshkin MA. Cobots: robots for collaboration with human operators. In: Proceedings of the ASME International Mechanical Engineering Congress and Exposition; 1996 Nov; Atlanta, GA. p. 433-439.
44. Javaid M, Haleem A, Singh RP, Rab S, Suman R. Significant applications of cobots in the field of manufacturing. Trends Cogn Sci. 2022;2(3):222-233.

doi:10.1016/j.cogr.2022.10.001.
45. Vojić S. Applications of collaborative industrial robots. Int Sci J Mach Technol Mater. 2022;3:96-104. Available from: https://stumejournals.com/journals/mtm/2020/3/96.full.pdf.
46. Moshagen M, Erdfelder E. Provides a-priori, post-hoc, and compromise power-analyses for structural equation models (SEM). Struct Equ Modeling. 2016;23(1):54-60. doi:10.1080/10705511.2014.950896.
47. Spitzer RL, Kroenke K, Williams JB. Validation and utility of a self-report version of PRIME-MD: the PHQ primary care study. JAMA. 1999;282(18):1737-1744. doi:10.1001/jama.282.18.1737.
48. American Psychiatric Association. Diagnostic and statistical manual of mental disorders: DSM-IV-TR. 4th ed., text revision. Washington, DC: American Psychiatric Association; 2000.
49. Spitzer RL, Kroenke K, Williams JB, Löwe B. A brief measure for assessing generalized anxiety disorder: the GAD-7. Arch Intern Med. 2006;166(10):1092-1097. doi:10.1001/archinte.166.10.1092.
50. Di Fabio A, Gori A. Measuring adolescent life satisfaction: psychometric properties of the satisfaction with life scale in a sample of Italian adolescents and young adults. J Psychoeduc Assess. 2015;1-6. doi:10.1177/0734282915621223.
51. Bernales-Turpo D, Quispe-Velasquez R, Flores-Ticona D, Saintila J, Ruiz Mamani PG, Huancahuire-Vega S, Morales-García WC. Burnout, professional self-efficacy, and life satisfaction as predictors of job performance in health care workers: the mediating role of work engagement. J Prim Care Community Health. 2022;13. doi:10.1177/21501319221101845.
52. Cobos-Sanchiz D, Del-Pino-Espejo MJ, Sánchez-Tovar L, Matud MP. The importance of work-related events and changes in psychological distress and life satisfaction amongst young workers in Spain: a gender analysis. Int J Environ Res Public Health. 2020;17(13):4697. doi:10.3390/ijerph17134697.
53. Jeong H, Syed R. Relationship between the use of IT and wellbeing: a literature review. In: Proceedings of the 2022 Northeast Association for Information Systems Conference; 2022 May 24-25; Virtual Conference.
54. Paliga M. The relationships of human-cobot interaction fluency with job performance and job satisfaction among cobot operators: the moderating role of workload. Int J Environ Res Public Health. 2023;20(6):5111. doi:10.3390/ijerph20065111.
55. Hoffman G. Evaluating fluency in human–robot collaboration. IEEE Trans Hum Mach Syst. 2019;49(3):209-218. doi:10.1109/THMS.2019.2904554.
56. Nomura T, Suzuki T, Kanda T, Kato K. Measurement of negative attitudes toward robots. Interact Stud. 2006;7(3):437-454. doi:10.1075/is.7.3.10nom.
57. Nenna F, Zanardi D, Orlando EM, Mingardi M, Buodo G, Gamberini L. Addressing trust and negative attitudes toward robots in human-robot collaborative scenarios: insights from the industrial work setting. In: Proceedings of the 17th International Conference on Pervasive Technologies Related to Assistive Environments; 2024 Jun. p. 259-264.
58. Müller-Abdelrazeq SL, Schönefeld K, Haberstroh M, Hees F. Interacting with collaborative robots—a study on attitudes and acceptance in industrial contexts.

In: Social robots: technological, societal and ethical aspects of human-robot interaction. 2019. p. 101-117. doi:10.1007/978-3-030-17107-0_7.
59. Bassi G, Orso V, Gamberini L. EPICOS: a semi-structured interview protocol for exploring the operator's perspective on collaborating with cobots and their impact on well-being in Industry 5.0. Suvremena Psihologija. 2023;70(Suppl 1):10-15.
60. Charalambous G, Fletcher S, Webb P. Identifying the key organisational human factors for introducing human-robot collaboration in industry: an exploratory study. Int J Adv Manuf Technol. 2015;81:2143-2155. doi:10.1007/s00170-015-7310-3.
61. Faccio M, Granata I, Menini A, Milanese M, Rossato C, Bottin M, et al. Human factors in cobot era: a review of modern production systems features. J Intell Manuf. 2023;34(1):85-106. doi:10.1007/s10845-021-01814-z.
62. Baumgartner M, Kopp T, Kinkel S. How anthropomorphic features and visual appeal influence users' trust in collaborative robots. Int J Soc Robot. 2022;14(3):405-421. doi:10.1007/s12369-020-00697-8.
63. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.

64. Benoit K, Watanabe K, Wang H, Nulty P, Obeng A, Müller S, et al. quanteda: an R package for the quantitative analysis of textual data. J Open Source Softw. 2018;3(30):774. doi:10.21105/joss.00774.

65. Bagheri B, Boyes H, Hung KK, Wu F, Basaeed A. A multi-level blockchain framework for smart city digital twin. Cities. 2022;123:103540. doi:10.1016/j.cities.2022.103540.

66. Smyth JM, Zawadzki MJ, Juth V, et al. Global life satisfaction predicts ambulatory affect, stress, and cortisol in daily life in working adults. J Behav Med. 2017;40:320–331. doi:10.1007/s10865-016-9790-2.

67. Liao S, Lin L, Chen Q, Pei H. Why not work with anthropomorphic collaborative robots? The mediation effect of perceived intelligence and the moderation effect of self-efficacy. Hum Factors Ergon Manuf. 2024;34(3):241-260. doi:10.1002/hfm.21005.

68. American Psychological Association. Subjective well-being. Available from: https://dictionary.apa.org/subjective-well-being. Accessed 2023 Nov 5.

69. De Vos S, Bockel-Rickermann C, Van Belle J, et al. Predicting employee turnover: scoping and benchmarking the state-of-the-art. Bus Inf Syst Eng. 2024. doi:10.1007/s12599-024-00898-z.

70. Ghislieri C, Molino M, Cortese CG. Work and organizational psychology looks at the fourth industrial revolution: how to support workers and organizations? Front Psychol. 2018;9:2365.

# Supplementary Files

# Figures

The conceptual model of a path analysis investigating the role of fluency in HRI and negative attitudes towards advanced production technologies between cognitive and affective well-being.