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THE NASA-TLX APPROACH TO UNDERSTAND WORKERS WORKLOAD IN HUMAN-ROBOT COLLABORATION

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Abstract
Human-robot collaboration (HRC) is becoming increasingly widespread in today's production systems, as it can contribute to achieving more efficient and flexible production systems. Given the growing importance of HRC, this paper addresses the significance of human workload in HRC. To study workers workload an experiment was conducted using NASA-TLX questionnaire. The experiment featured two scenarios involving the same operation but varying robot motion parameters. Recognizing that individual differences contribute to success of collaboration, the experiment considered worker utilization in relation to robot motion parameters. To ensure the credibility of the experimental results, the robot motion parameters were adjusted to each individual in order to achieve the same conditions and utilization at all participants. Results revealed that worker utilization, in conjunction with robot motion parameters significantly influenced worker workload. The results highlight the need for personalized guidelines in collaborative workplaces that emphasize individual differences in abilities, skills and personalities to increase overall well-being and robot and worker productivity.

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Key Words: Human-Robot Collaboration, Industry 5.0, NASA-TLX, Safety Awareness, Worker Well-Being, Worker Workload

1. INTRODUCTION

In recent years, customer orders have increased in complexity and individuality. The modern consumer expects products that are tailored to their individual needs and delivered with unprecedented speed. Customer demands are putting additional pressure on manufacturers to become highly flexible and adaptable. In order to meet these demands, a redesign of production systems and processes is essential. When redesigning systems, processes and layouts, it is important to achieve both flexibility and efficiency, which contributes to company competitiveness on the global market. Companies in almost all industries have realized that it is necessary to invest in new technologies and digital strategies in order to remain competitive [1]. The development of Industry 4.0 and related technologies such as Internet of Things, Cyber-Physical Systems, Digital Twins, advanced robots (industrial and collaborative) and automation systems has the potential to create more flexible and efficient production systems through the use of advanced technologies and their digital capabilities [2]. Researchers and engineers are constantly looking to optimize systems, either by using new technologies or simply by reconfiguring existing workstations, parameters, etc. The implementation of new technologies can be expensive and also dangerous, changes and their contribution to overall performance need to be carefully studied before execution. Simulation modelling tools help researchers and engineers to find optimal solutions and solve all kinds of problems, from limited capacities, resource utilization, workflows, costs, etc. [3, 4]. With the enhanced digitalization level in Industry 4.0, simulation tools are becoming more popular among engineers as the capabilities of such tools increase with the prospects of advanced technologies. The use of the IoT platform enables the networking of devices and the transfer of real-time data from general devices and sensors into digital twins. Models fed with real-time data and supported by artificial intelligence (AI) methods help engineers to achieve optimized production systems [5]. Big data is also referred to as a prospect technology in Industry 4.0, as large amounts of data are collected

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from smart sensors and stored in cloud systems. The ability to collect and store such amounts of data allows engineers to simulate and replicate processes and analyse possible scenarios based on real-world situations [6]. It is clear that companies need to integrate advanced technologies and make their systems technology-driven in order to meet complex customer demands and trends in the modern world. Technological transition brings many advantages, but the biggest disadvantage is that human aspects and society are often forgotten. To address these concerns, researchers are proposing a new concept of industry evolution Industry 5.0 that emphasizes the importance of human-centric, resilience and sustainability as a complement to the existing goals of Industry 4.0 [7]. Greater human involvement and the design of human-centred systems will contribute to more human-machine interactions [8].

In recent years, robots have been deployed with the aim of replacing workers and contributing to higher productivity and therefore higher profits. However, as trends and demands in the global market have changed and systems that are more dynamical are required, the development of collaborative robots and collaborative workplaces, where humans and robots can work side by side, present a solution. Collaborative workplace consists of a human and a robot working together to achieve a common goal. The main idea behind collaborative workplaces is to combine the capabilities of humans and robots, with the human contributing to flexibility, intelligence and problem solving, while the robot provides strength, precision and repeatability [9]. Although collaborative robots have built-in force and torque sensors to prevent injuries, the implementation of such a robot needs to be studied in detail as a human and a robot share the same workspace [10]. Collaborative workplaces are an important topic in the modern world of advanced systems, but for an efficient implementation of a collaborative workplace, aspects of sustainability need to be investigated. Sustainability is an extended term that consists of an economic, an environmental and a social aspect [11]. In engineering, the main focus has been on economic and environmental aspects as researchers propose different methods, optimization techniques and algorithms to achieve cost savings and a friendlier environment [12]. In recent researches and with the emerging Industry 5.0, the social aspect is becoming more and more prominent. Researchers are proposing various solutions, proposals, designs and calculations that are more human-oriented in order to achieve a people-friendly environments, higher safety, suitable health conditions and so on [13-15]. Since collaborative workplaces consist of a human, a robot and a shared workspace, the social aspect of humans needs to be addressed.

After a careful review of existing research, it was found that the social aspects in HRC is often described only by the physical health and condition of the human, but the mental health of the human is still often overlooked, although more and more people suffer from the consequences of psychological factors [16]. Based on the findings, the research question was designed as how the different worker utilization during the HRC affects the physical and mental workload of worker. In order to present the research problem appropriately, the paper is structured as follows: Section 2 presents the research problem. Section 3 describes the experimental setup consisting of the workplace design, the operation design and the structure of the experiment. Section 4 presents the experimental results and a comparison between the scenarios. The final section, Section 5, summarizes the results and discusses the limitations and opportunities for future work.

2. PROBLEM DESCRIPTION

In the era of rapid technological advancement, the HRC has emerged as a new technology that has the potential to transform industry and the way we work. With the use of robot capabilities and human intelligence, we are able to create optimized and intelligent manufacturing systems that meet both, market demands and worker needs. HRC free workers from dangerous, monotonous and harmful tasks, and allow them to focus on more creative and complex tasks that make a greater contribution to the production system. HRC has great potential for more efficient and productive systems, but the coexistence of a robot and a worker in a shared workspace requires a more detailed study of workplace safety and the impact of a robot on a human in terms of their workload and well-being. Among the many existing variables (proximity of the robot, types of movement, size of the robot, etc.) that can potentially influence the HRC efficiency, the parameters of the collaborative robot are of particular interest to us. The results of previous research provide interesting findings regarding the effects of collaborative robot parameters on a worker and a system. Higher defined collaborative robot parameters not only contribute to shorter collaborative robot processing times, but also to workers assembly times [17]. Such a finding suggests setting the parameters as high as possible to achieve higher productivity, but on the other hand, the system efficiency remains the same or even lower with the higher defined parameters due to the limitations of the system and the human [18]. To properly determine the parameters of the collaborative robot, both the system and the human need to be carefully studied.

In the presented paper, the impact of collaborative robot's parameters (consequently worker utilization) on the workers workload is investigated using the NASA Task Load Index (NASA-TLX) questionnaire [19]. With the study conducted and the use of the subjective questionnaire, the importance of human well-being and workload in HRC is presented.

2.1 Human-robot collaboration

Human-robot collaboration is becoming an increasingly important topic in today's industry. The availability of HRC in a shared work environment has contributed to many opportunities in terms of improved productivity, efficiency and flexibility. Researchers have categorized HRC into four types based on safety requirements and the level of collaboration between humans and robots [20]. The first type is caged cell, where robots and workers are separated by a safety fence and the level of collaboration between them is practically zero. The second type is the coexistence, where collaborative robot and the worker share the same workspace, but a collaborative workspace does not exist between them. In the third and fourth type of a HRC, a robot and a worker have a shared collaborative workspace. The only difference is that in the third type (cooperation) they do not simultaneously perform tasks in the shared workspace, as is the case in the fourth type (direct collaboration).

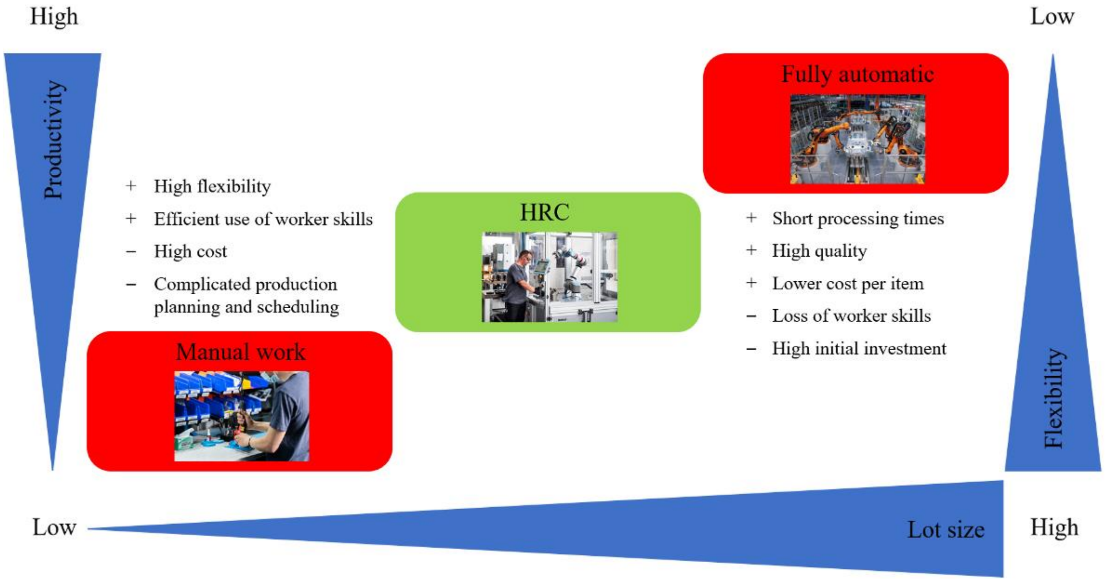


Figure 1: The prospects of human-robot collaboration in production systems.

Before the development of collaborative robots and collaborative workplaces, the work was done either manually or with the help of automation. Both types of work have advantages and disadvantages, shown in Fig. 1 and are suitable under certain conditions. The use of automation contributes to shorter processing times, lower product costs, higher reliability, higher precision and a higher number of finished products. On the other hand, work performed manually enables the completion of more complex products, increase the flexibility of a process and contribute to the full utilization of workers skills. With the changing aspects of today's world, the demands for more and more complex and dynamic systems are increasing. Collaborative workplaces, consequently HRC, can be a potential solution because they combines strengths and advantages of humans and robots. Although the use of HRC has enormous potential, there effects on the production system and the worker must be properly considered, especially in terms of worker safety.

2.2 Worker safety awareness

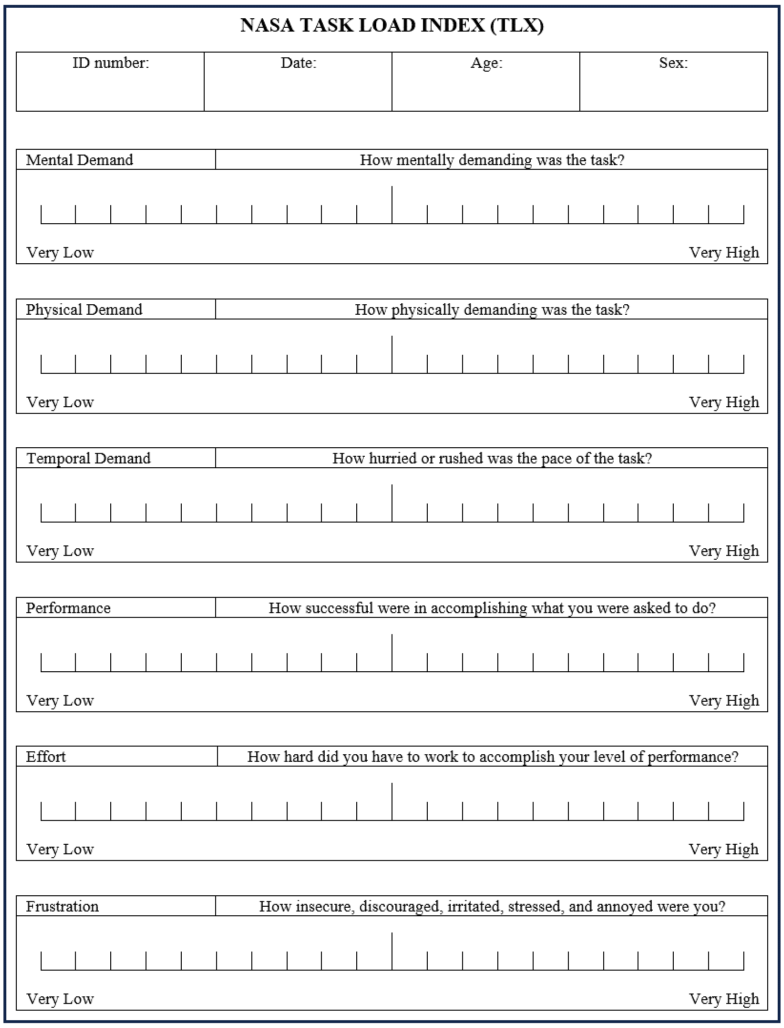
The human safety is, and remains one of HRC's top priorities. The possibility of potential physical contact between a robot and a worker highlights the importance of worker safety awareness. Although a collaborative robot has built-in safety features that allow it to work with workers in a shared workspace, it is inevitable to avoid direct contact between a worker and a robot. To prevent dangerous contact between them or an accident, safety standards must be met. For implementation of robots, standards EN ISO 10218-1, EN ISO 10218-2 and ISO/TS 15066 were established. The technical specification ISO/TS 15066 is specifically designed for collaborative robots and provides additional guidance on their design, safety requirements and risk assessment [21]. The technical specification propose four different methods (safety-rated monitored stop, hand guidance, speed and distance monitoring, power and force limitation) with additional guidelines on risk assessment, safety distance, force and pressure limits in the certain body area to ensure the safety of a collaborative operation. Safety standards provide a good starting point, but HRC is not only about the machine safety factor, but also about the human risk factor. Most research and their guidelines are concern with the physical health or physical workload of humans, while the mental workload has often been neglected. Lately, researchers have started to focus also on the mental health of workers and their well-being during HRC. The results show that human mental health is also affected, as parameters such as speed and acceleration, the distance between the robot and the worker and the acknowledgment of robot movements contribute to a higher perceived human mental workload [22]. As results indicate, with the establishment of Industry 5.0 a human role is going to be even more significant. To provide safe, sustainable and efficient human-centred systems, specific guidelines and instructions regarding workers workload and their well-being will be needed.

2.3 NASA-TLX questionnaire

The NASA-TLX questionnaire shown in Fig. 2 is a standardized tool for measuring people's subjective workload. The questionnaire was originally developed by the Human Performance Group at the NASA Ames Research Center and was initially called the NASA Bipolar Rating Scale. The questionnaire was later redesigned due to its impractical use as some of the subscales were found to be irrelevant or redundant to workload. The subscales of the original questionnaire were revised, combined, deleted or added, and thus the NASA-TLX was developed on the basis of six dimensions (physical demand, mental demand, temporal demand, performance, effort and frustration) [19].

The NASA-TLX questionnaire consists of two parts. In the first part, participants subjectively rate each dimension on a scale of 0 to 100 points in 5-point increments. The higher the score, the greater the influence of the evaluated dimension is. The second part contains the weighting of the dimensions, which indicates the importance of the individual dimensions. The weighting can be done in different ways and depends on the decision of the experimenter. It can be made based on the results of fifteen pairwise comparisons of the six dimensions, based on the feeling of the participants, based on the choice of the experimenter or weights just evenly distributed across the dimensions. If the weighting is done by the participants, they choose the weight for each dimension based on the importance of each dimension and its contribution to the overall workload. When weighting is done by a rater, the goal is to place a specific emphasis on a particular dimension.

The scale shown in Table I was used to evaluate the impact of each factor and also the final workload. When using the NASA-TLX questionnaire it should be noted that the obtained results are based on subjective assessments, which may lead to misleading conclusions.



NASA TASK LOAD INDEX (TLX)

ID number:	Date:	Age:	Sex:

Mental Demand	How mentally demanding was the task?
Very Low	Very High

Physical Demand	How physically demanding was the task?
Very Low	Very High

Temporal Demand	How hurried or rushed was the pace of the task?
Very Low	Very High

Performance	How successful were in accomplishing what you were asked to do?
Very Low	Very High

Effort	How hard did you have to work to accomplish your level of performance?
Very Low	Very High

Frustration	How insecure, discouraged, irritated, stressed, and annoyed were you?
Very Low	Very High

Figure 2: The NASA TLX questionnaire [19].

Table I: The interpretation value of the NASA-TLX [23].

Workload	Value
Low	0-9
Medium	10-29
Somewhat high	30-49
High	50-79
Very high	80-100

3. EXPERIMENT DESCRIPTION

To study the impact of different collaborative robot parameters (worker utilization) on a worker workload and well-being, we need to design our own collaborative workplace and a collaborative operation. The experiment was conducted in a laboratory environment, so the equipment used, a workstation and an operation had to be adapted to the laboratory environment to ensure safe and suitable conditions for conducting the experiment.

3.1 Collaborative workplace description

The collaborative workplace is shown in Fig. 3 and consists of a collaborative robot UR3e ① (the smallest version of the UR collaborative robots, ideal for tests and experiment in limited environments), a collaborative gripper Robotiq 2F-85 ② (two-finger gripper with the range of 85 mm), a worktable ③, a switch with light indicators ④ and a button ⑤, a preparation area ⑥, and a buffer of semi-finished products 1 ⑦, 2 ⑧, 3 ⑨ and finished products ⑩.

Legend:
① collaborative robot
② collaborative gripper
③ worktable
④ switch with light indicators
⑤ button
⑥ preparation area
⑦ buffer of semi-finished products 1
⑧ buffer of semi-finished products 2
⑨ buffer of semi-finished products 3
⑩ buffer of finished products

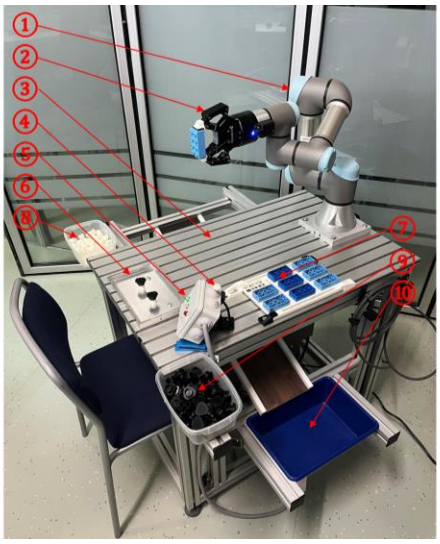


Figure 3: Layout of a collaborative workplace adapted to the laboratory environment.

3.2 Collaborative operation description

The use of LEGO bricks offers many possibilities in the phase of design as they are simple to assemble, there are many variants and everyone knows them, so no special instructions and introduction is required. The aim of the study was to study the effects of different workers utilization on their workload and well-being in HRC. However, because the LEGO bricks are so simple to assemble, it was difficult to achieve a specific level of worker utilization. In order to achieve the research objective and reach an appropriate worker's utilization during collaborative operation, the LEGO bricks need to be combined with our self-designed parts (semi-finished product 2 and semi-finished product 3) as seen in Fig. 4.

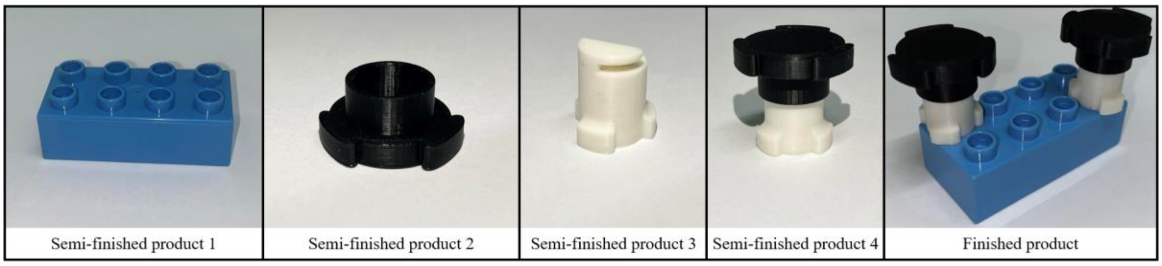


Figure 4: Assembly product parts.

In the initial phase of a collaborative operation, the collaborative robot ① picked up a semi-finished product 1 and brought it to the assembly point. In the meantime, the worker had to assemble two semi-finished products 4, consisting of a semi-finished product 2 and a semi-finished product 3. When the collaborative robot ① came to the assembly point, the light on the indicator turned green ④, which allowed the worker to attach two semi-finished products 4 to the semi-finished product 1. After a finished product was assembled, the worker pressed a button ⑤ to confirm the continuation of the operation (a red light turned on ④). The collaborative robot ① moved the finished product into the buffer of finished products ⑩ and a worker started preparing for a new cycle.

3.3 Experiment design

The experiment was divided into two parts. The first part was the introduction, in which the worker familiarized himself with the NASA-TLX questionnaire, the collaborative robot and its operation. The second part was the collaboration in which the worker collaborated with the collaborative robot. To test our research question of how the worker utilization impact on their workload and well-being, the second part (collaboration) consisted of two 10 min long scenarios. In the first scenario, worker utilization was predetermined to 60 % and in the second scenario to the 100 %. Each scenario was followed by a 5 min break to relax and to answer the NASA-TLX questionnaire to assess the perceived workload.

Because as human beings we are different and so are our skills and abilities, the collaborative robot parameters need to be defined for each individual in order to achieve the same worker utilization (w_{util}) for all participants. To define collaborative robot parameters that are suitable for each individual, an average worker final assembly time (t_{fa}) and an average worker preparation time (t_p) were needed. To determine the average times a pre-test was conducted, where each participant had to assemble as many semi-finished products 4 for 90 s as possible before the start of the experiment. An average worker preparation time (for parts collecting and pre-assembly) for the semi-finished products 4 was calculated from the number of assembled semi-finished products 4. The worker working time during the collaborative operation is made up of preparation time and final assembly time, which is required for joining of semi-finished products 4 with the semi-finished product 1. The average final assembly time was determined in advance based on preliminary tests that were carried out in the laboratory and was not calculated for each individual, as the differences between the test subjects were too small. Once both times were determined, a robot operating time (t_r) could be calculated using Eq. (1) to ensure the desired worker utilization. The calculated robot operating time was then converted into the parameters of the collaborative robot.

$$t_r = \frac{t_p + t_{fa}}{w_{util}} - t_{fa} \tag{1}$$

4. RESULTS

The experiment lasted about 60 min, depending on the participants and their abilities. Forty-four people took part in the experiment, thirty-three of whom were men and eleven women. The average age of the participants was 25.5 years with a standard deviation of 2.95 years. As mentioned earlier, the participants had to answer the NASA-TLX questionnaire after each scenario. The scores obtained by all participants are shown in Table II. Abbreviations of dimensions have been used for the ease of presentation: *MD* – mental demand, *PD* – physical demand, *TD* – temporal demand, *P* – performance, *E* – effort, *F* – frustration, *AV* – average score of all dimensions.

Table II: Experimental results of each participant.

	Scenario 1 (worker utilization: 60 %)							**Scenario 2** (worker utilization: 100 %)						
ID	*MD*	*PD*	*TD*	*P*	*E*	*F*	*AV*	*MD*	*PD*	*TD*	*P*	*E*	*F*	*AV*
1	25	35	20	15	50	45	31.7	70	85	95	10	95	90	74.2
2	15	10	30	5	25	20	17.5	15	30	60	10	45	20	30.0
3	15	15	5	15	5	5	10.0	80	80	90	25	70	55	66.7
4	10	10	25	10	10	10	12.5	80	55	90	35	100	90	75.0
5	5	5	5	5	5	5	5.0	100	100	100	35	85	80	83.3
6	5	10	10	35	10	30	16.7	15	25	90	5	25	10	28.3
7	10	15	15	5	10	5	10.0	55	75	80	65	65	60	66.7
8	5	10	10	5	5	5	6.7	5	15	55	30	10	10	20.8
9	5	5	50	5	10	5	13.3	20	30	65	5	55	10	30.8
10	20	10	10	5	5	35	14.2	25	20	95	5	20	20	30.8
11	45	15	25	20	15	15	22.5	80	65	75	10	55	50	55.8
12	20	10	15	20	45	15	20.8	75	55	80	35	65	25	55.8
13	15	10	20	20	15	15	15.8	20	45	65	30	55	30	40.8
14	15	10	15	5	5	10	10.0	65	55	85	70	90	70	72.5
15	10	15	15	55	20	10	20.8	20	30	70	50	35	15	36.7
16	10	15	10	50	15	5	17.5	65	70	75	65	70	65	68.3
17	20	30	10	45	30	15	25.0	55	70	75	50	55	55	60.0
18	25	10	15	50	15	5	20.0	25	30	90	50	35	15	40.8
19	15	20	20	15	10	10	15.0	40	60	95	40	85	45	60.8
20	20	50	20	50	55	35	38.3	60	75	80	50	80	55	66.7
21	35	45	45	45	55	15	40.0	65	65	85	45	75	55	65.0
22	20	5	25	30	10	5	15.8	20	10	60	30	30	5	25.8
23	30	30	35	20	30	15	26.7	70	75	85	45	75	55	67.5
24	30	10	20	20	40	20	23.3	75	60	85	40	80	90	71.7
25	10	10	0	5	10	10	7.5	50	35	100	70	85	35	62.5
26	20	15	20	15	15	10	15.8	50	50	95	30	55	85	60.8
27	25	10	20	10	35	15	19.2	40	25	95	60	75	65	60.0
28	0	0	0	5	5	0	1.7	0	5	65	25	75	25	32.5
29	30	10	20	10	35	15	20.0	50	30	85	75	75	70	64.2
30	20	20	15	25	30	20	21.7	40	50	65	35	45	20	42.5
31	0	0	20	15	10	25	11.7	50	45	85	40	70	40	55.0
32	5	5	15	10	5	5	7.5	35	30	30	20	60	20	32.5
33	20	25	20	15	10	5	15.8	55	60	95	40	85	35	61.7
34	20	10	15	15	15	10	14.2	60	40	70	30	70	50	53.3
35	5	5	15	0	35	5	10.8	25	15	95	30	95	10	45.0
36	5	15	15	25	30	5	15.8	15	25	40	35	50	35	33.3
37	20	15	35	25	30	45	28.3	65	70	90	55	75	85	73.3
38	15	25	10	10	35	25	20.0	55	60	85	25	60	50	55.8
39	5	10	5	5	5	10	6.7	10	25	70	40	75	25	40.8
40	15	5	15	20	35	35	20.8	80	55	75	15	65	90	63.3
41	15	15	20	40	15	15	20.0	45	55	75	30	70	65	56.7
42	20	10	15	15	25	5	15.0	85	65	90	60	85	55	73.3
43	5	5	15	5	15	5	8.3	20	25	100	25	70	5	40.8
44	15	0	0	0	10	15	6.7	85	85	100	25	100	70	77.5

After the experiment, an average score was calculated for each dimension. In our case, the weights were distributed evenly across all dimensions, as no prior assumptions were to be made about the importance of the individual dimensions. To investigate our research question of how the different worker utilization affect the worker workload, a comparison was made between the results of the individual scenario, which is shown in Fig. 5.

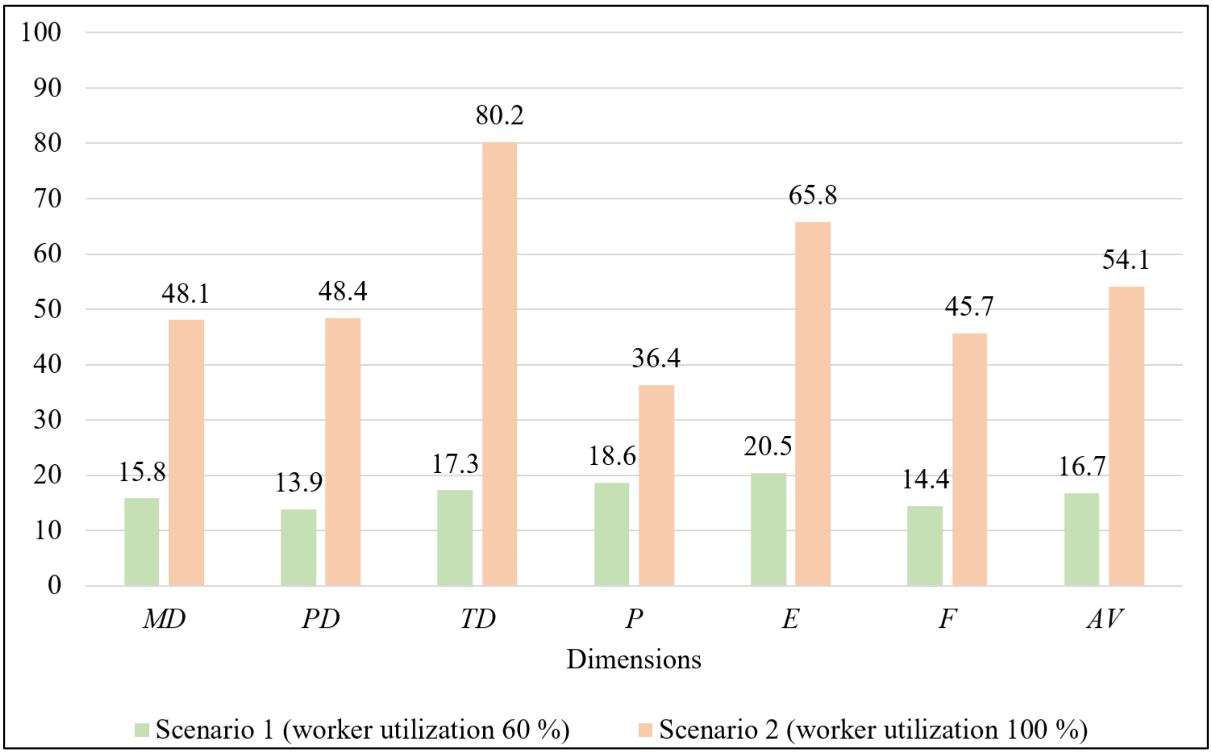


Figure 5: Comparison of average dimension results in each of the scenarios.

According to the questionnaire, an increase can be seen in all dimensions. The greatest difference occurs in the dimension *TD* (62.9 %), followed by *E* (45.3 %), *PD* (34.5 %), *MD* (32.3 %), *F* (31.3 %) and *P* (17.8 %). On average, the participants' total workload increases by 34.7 %, which clearly indicates that the higher worker utilization contributes to a higher worker workload. As already mentioned, the largest difference was achieved in the *TD* dimension and the smallest difference in the *P* dimension. Temporal demand is related to the pace of the task and the time pressure that participants feel during work. The main reason for the highest difference in *TD* between the scenarios, according to the participants' responses was that the movement of the collaborative robot was too fast in the second scenario, so the collaborative robot had to wait for the workers to complete the assembly with it. Watching the collaborative robot waiting for them made them feel nervous and frustrated about not being good enough and put them under time pressure to complete the operation properly.

Although at dimension *P* the smallest difference between the scenarios was obtained, the increase from the first scenario to the second scenario shows that participants rated their performance better when the robot cycle was shorter. Rating performance is difficult, especially for the participants of the experiment who do not know what an optimal result may be, but a higher rating of performance in the second scenario is likely indicated by the effort they put in, when collaborating at faster motion of a collaborative robot. The results also confirmed the statement mentioned above that mental health is as important as physical health, as the average scores of *MD* and *PD* are similar in each scenario. Although the results confirmed an increase in workers workload at higher workers utilization, and that participants selected *TD* as the most influential dimension and *P* as the least influential, it must be considered that NASA-TLX is a subjective questionnaire where dimensions can be interpreted differently by participants and the boundaries between dimensions cannot be fully drawn.

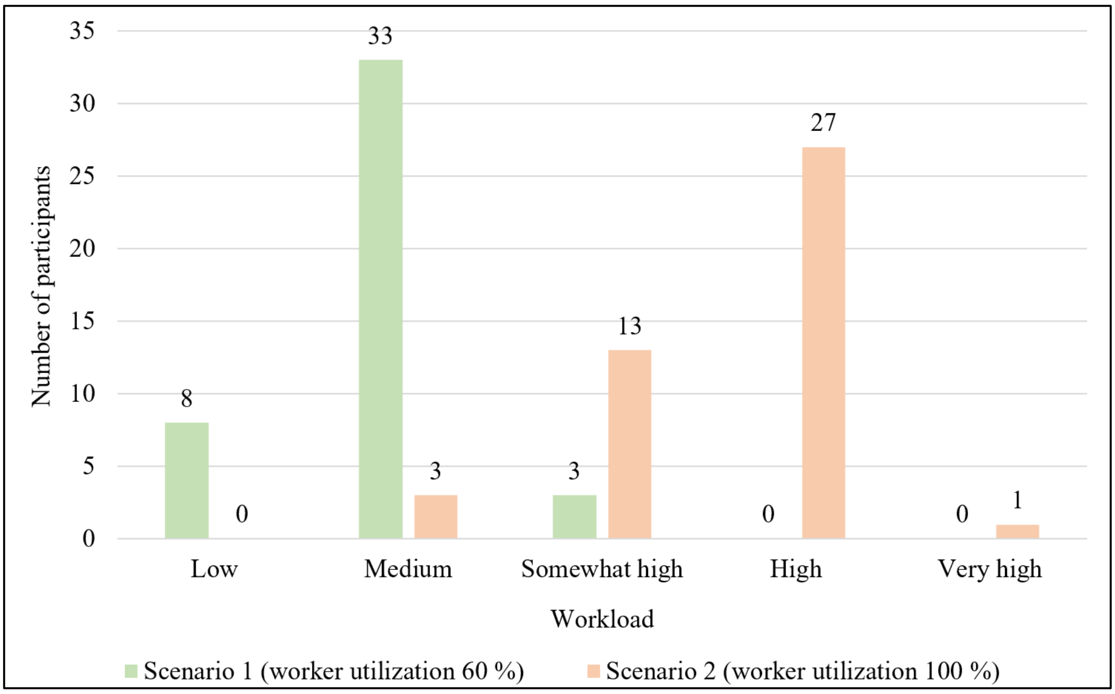


Figure 6: Comparison of participant's workload results in each of the scenarios.

To evaluate the overall workload of the participants in each scenario of the experiment, the participants were distributed into the classes according to the scale in Table I. In the first scenario, thirty-three participants experienced a medium workload, eight participants experienced a low workload and three participants experienced a somewhat high workload. As the collaborative robot parameters and consequently worker utilization increased in the second scenario, the workload of the participants also increased, as can be seen in Fig. 6. In the second scenario, twenty-seven participants were classified at high workload, thirteen participants were classified at somewhat high, three participants were classified at medium and one participant was classified at very high. The results clearly indicate that the worker utilization when working with the collaborative robot makes an important contribution to the worker workload. As the results show, it will become increasingly important to achieve the right level of workload and to determine the limits that need to be fulfilled during the HRC.

5. DISCUSSION AND CONCLUSION

This paper emphasizes the importance of the worker workload when collaborating with the robot. HRC consists of a collaborative robot, a human and a correlation between them which contribute to the overall success. According to previous research [17], the motion parameters of a collaborative robot have an impact on worker productivity and their capabilities. Although the impact of the parameters has been confirmed from a productivity perspective, their impact on worker well-being and workload has been unknown. Since the motion parameters of a collaborative robot can have different effects on humans, it was decided that for an adequate study of the workers workload, the workers utilization need to be taken into account.

In order to study the workload of the workers, an experiment was designed consisting of two scenarios with the same operation but different collaborative robot motion parameters and consequently different worker utilization. In the first scenario of the experiment, the motion parameters of a collaborative robot were defined to ensure a worker utilization of 60 % and in the second scenario to ensure worker utilization of 100 %. To measure a worker workload the NASA-TLX questionnaire was used after each scenario. Based on the responses, a comparison study of worker's workload between the scenarios was carried out. The results showed that the worker utilization in correlation with the motion parameters of a collaborative robot influences the workload of the worker. When comparing the scenarios, the average workload in the first scenario was 16.7 % (worker utilization 60 %) and the average workload in the second scenario was 54.1 % (worker utilization 100 %). Fully utilization of a worker in average contributed to a 34.7 % increase in worker workload. Participants were also classified into levels based on their overall workload according to the scale shown in Table I. In the first scenario, 75 % of participants perceived a medium workload, 18 % a low workload and 7 % a somewhat high workload. In the second scenario, the perceived workload increased for all participants compared to the first scenario. According to the classification, 61 % of the participants felt a high workload, 30 % a somewhat high workload, 7 % a medium workload and 2 % a very high workload. Results indicates that the perceived workload has moved from a medium to a high level at the majority of participants. According to the results the impact of all six dimensions increased with the increased worker utilization. The greatest difference of 62.9 % occur at the dimension *TD* (temporal demand), which highlights the time pressure that participants felt.

HRC is still relatively unexplored, especially in the case of humans. In the near future, guidelines for human workload and well-being in HRC need to be specifically developed and considered. It is necessary to realize that a human role represent the centre of a collaborative workplace and that their role will only get more important in modern world and systems, so settings and limits will have to be specifically designed and customized to individual personalities. In future work, we aim to study a sustainability perspective of collaborative workplaces, especially the social aspect. In order to obtain more relevant results about human well-being and workload when collaborating with robots, subjective methods will be supported by objective methods.

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REFERENCES

[1] Martinčević, I.; Kozina, G. (2021). Influence of digital technologies and its technological dynamics on company management, *Technical Gazette*, Vol. 28, No. 4, 1262-1267, doi:10.17559/TV-20200924091906

[2] Bajic, B.; Suzic, N.; Simeunovic, N.; Moraca, S.; Rikalovic, A. (2020). Real-time data analytics edge computing application for Industry 4.0: the Mahalanobis-Taguchi approach, *International Journal of Industrial Engineering and Management*, Vol. 11, No. 3, 146-156, doi:10.24867/IJIEM-2020-3-26

[3] Malega, P.; Rudy, V.; Kanász, R.; Gazda, V. (2020). Decentralized optimization of the flexible production lines, *Advances in Production Engineering & Management*, Vol. 15, No. 3, 267-276, doi:10.14743/apem2020.3.364

[4] Xu, N.; Hou, X. Y.; Jia, N. (2022). Optimization of multi-stage production scheduling of automated production, *International Journal of Simulation Modelling*, Vol. 21, No. 1, 160-171, doi:10.2507/IJSIMM21-1-CO3

[5] Wang, N.; Li, X. J.; Nie, H. (2021). Digital production control of manufacturing workshop based on Internet of Things, *International Journal of Simulation Modelling*, Vol. 20, No. 3, 606-617, doi:10.2507/IJSIMM20-3-CO15

[6] Ghadge, A.; Kara, M. E.; Moradlou, H.; Goswami, M. (2020). The impact of Industry 4.0 implementation on supply chains, *Journal of Manufacturing Technology Management*, Vol. 31, No. 4, 669-686, doi:10.1108/JMTM-10-2019-0368

[7] Saniuk, S.; Grabowska, S.; Straka, M. (2022). Identification of social and economic expectations: contextual reasons for the transformation process of Industry 4.0 into the Industry 5.0 concept, *Sustainability*, Vol. 14, No. 3, Paper 1391, 20 pages, doi:10.3390/su14031391

[8] Özdemir, V.; Hekim, N. (2018). Birth of Industry 5.0: making sense of big data with artificial intelligence, "The internet of things" and next-generation technology policy, *A Journal of Integrative Biology*, Vol. 22, No. 1, 65-76, doi:10.1089/omi.2017.0194

[9] Gervasi, R.; Mastrogiacomo, L.; Franceschini, F. (2020). A conceptual framework to evaluate human-robot collaboration, *The International Journal of Advanced Manufacturing Technology*, Vol. 108, No. 3, 841-865, doi:10.1007/s00170-020-05363-1

[10] Kumar, S. P. (2020). *Dynamic Speed and Separation Monitoring with On-Robot Ranging Sensor Arrays for Human and Industrial Robot Collaboration*, PhD Thesis, Rochester Institute of Technology, New York

[11] Ojstersek, R.; Buchmeister, B. (2020). Simulation modeling approach for collaborative workplaces' assessment in sustainable manufacturing, *Sustainability*, Vol. 12, No. 10, Paper 4103, 18 pages, doi:10.3390/su12104103

[12] Sherfudeen, S. S.; Athinamilagi, M.; Venkataramanujam, J. (2022). Optimization techniques for green layout design in manufacturing industries: a meta-heuristic analysis, *Strojniski vestnik – Journal of Mechanical Engineering*, Vol. 68, No. 11, 683-692, doi:10.5545/sv-jme.2022.321

[13] Dujmešić, N.; Bajor, I.; Rožić, T. (2018). Warehouse processes improvement by pick by voice technology, *Technical Gazette*, Vol. 25, No. 4, 1227-1233, doi:10.17559/TV-20160829152732

[14] Robla-Gomez, S.; Becerra, V. M.; Llata, J. R.; Gonzalez-Sarabia, E.; Torre-Ferrero, C.; Perez-Oria, J. (2017). Working together: a review on safe human-robot collaboration in industrial environments, *IEEE Access*, Vol. 5, 26754-26773, doi:10.1109/ACCESS.2017.2773127

[15] Karanikas, N.; Melis, D. J.; Kourousis, K. I. (2018). The balance between safety and productivity and its relationship with human factors and safety awareness and communication in aircraft manufacturing, *Safety and Health at Work*, Vol. 9, No. 3, 257-264, doi:10.1016/j.shaw.2017.09.001

[16] Escalante, D. C. The silent killer: revealing the harsh truths of mental illness and its deadly consequences, from *https://www.londonspring.org/the-silent-killer-revealing-the-harsh-truths-of-mental-illness-and-its-deadly-consequences/*, accessed on 14-05-2023

[17] Javernik, A.; Buchmeister, B.; Ojstersek, R. (2022). Impact of cobot parameters on the worker productivity: optimization challenge, *Advances in Production Engineering & Management*, Vol. 17, No. 4, 494-504, doi:10.14743/apem2022.4.451

[18] Ojstersek, R.; Buchmeister, B.; Javernik, A. (2023). The importance of cobot speed and acceleration on the manufacturing system efficiency, *Procedia Computer Science*, Vol. 217, 147-154, doi:10.1016/j.procs.2022.12.210

[19] National Aeronautics and Space Administration. NASA TLX Paper/Pencil Version, from *https://humansystems.arc.nasa.gov/groups/TLX/tlxpaperpencil.php*, accessed on 14-05-2023

[20] Zhang, A. ABB's Cobot Portfolio-Customer Presentation, from *https://s.sick.com/at-en-robot-roadshow-2022-documents*, accessed on 14-05-2023

[21] International Organization for Standardization (2016). *Robots and Robotic Devices: Collaborative Robots, ISO/TS 15066:2016*, International Organization for Standardization, Geneva

[22] Arai, T.; Kato, R.; Fujita, M. (2010). Assessment of operator stress induced by robot collaboration in assembly, *CIRP Annals*, Vol. 59, No. 1, 5-8, doi:10.1016/j.cirp.2010.03.043

[23] Prabaswari, A. D.; Basumerda, C.; Utomo, B. W. (2019). The mental workload analysis of staff in study program of private educational organization, *IOP Conference Series: Materials Science and Engineering*, Vol. 528, Paper 012018, 6 pages, doi:10.1088/1757-899X/528/1/012018