Human-centric experimental analysis of the impact of product variety on operator perceived workload and performance in manual assembly

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Abstract: The increasing variety of products in modern production systems adds complexity to the assembly process and places greater demands on operators, particularly in manual assembly settings. In manual assembly environments with high product variety, operators experience increased perceived workload, which can affect their efficiency and work quality. Therefore, this paper examines how product variety affects the perceived workload of operators in these environments. The research was conducted experimentally in a controlled laboratory environment using a case study involving the assembly of products made from LEGO components. Objective performance indicators were monitored, including assembly time, productivity, and the number of defective products, while perceived workload was assessed using the NASA-TLX questionnaire. The results indicate that increased product variety leads to a significant growth in perceived workload, particularly in the dimensions of mental demand, effort, and frustration. However, the decrease in productivity is not proportional to the increase in load. These findings highlight the importance of considering the human factor in the design of assembly systems, in line with the principles of Industry 5.0.

Keywords: *operator's perceived workload; manual assembly; NASA-TLX; product variety; experimental analysis; human-centric*

1. Introduction

Modern manufacturing systems must be flexible to meet growing market demands for customizable and individualized products. The increase in product variety offered by manufacturing companies directly results from these demands. This growth in variety increases the complexity of manufacturing processes. To remain competitive and ensure profitability, companies must systematically manage this complexity. The assembly process, a key phase that enables cost-effective product variety, is one of the main manufacturing processes significantly affected by the shift from mass production to mass customization [1].

Despite growing interest in automating manufacturing processes, including assembly, manual assembly remains common in many industrial contexts [2], [3]. This is because systems involving human participation offer greater flexibility than fully automated systems [4], especially when product variants change frequently. In manufacturing systems with high product variety, particularly in manual assembly, operators face additional demands compared to assembling a single standardized product or a set of products with uniform assembly processes. In these systems, operators must monitor more information, adapt to different product variants, and make decisions within limited time. These conditions can increase operators' perceived workload.

Perceived or subjective operator workload is most often defined as the individual or subjective experience of effort an operator feels while performing a specific task [5], [6]. The importance of

humans as key participants in the production process has been further recognized by the development of the Industry 5.0 paradigm, which, along with technological progress, places humans, their work experience, and well-being at the centre. This approach emphasizes balancing technological efficiency with human capabilities, with particular attention to working conditions and operator strain. Accordingly, Vitti et al. [7] identify operator workload as one of the key challenges of Industry 5.0.
In accordance with the above, this paper examines the presence and influence of perceived load on operators during manual assembly of various products. The research is based on an experimental analysis in which objective indicators of assembly success (product assembly time, productivity, and number of defective products) were monitored, while operators' perceived workload was assessed using the NASA-TLX questionnaire. The results enable analysis of the relationship between operators' perceived workload and changes in their performance. In this way, the study contributes to a better understanding of the influence of product variety in the context of manual assembly.

2. Experimental methodology

To examine the presence and influence of perceived load on operators during manual assembly of various products, an experimental study was conducted in controlled laboratory offices within the Learning Factory at the Faculty of Electrical Engineering, Mechanical Engineering, and Naval Architecture, University of Split. The Learning Factory is a controlled industrial environment that simulates real production processes and enables research, education, and experimentation without the risks and limitations of actual production [8]. The experiments were conducted at a single workstation with two operators who maintained fixed roles across all seven observed sequences. The same operator performed the manual assembly process for all sequences, while the other served as an observer, recording assembly times and conducting quality control of the finished products. After assembling each sequence, the operator who performed the manual assembly completed the NASA-TLX questionnaire, which was used to record the perceived load of the operator, i.e., perceived complexity. The experimental setup, as well as the structure and order of the assembly sequences, are described in the following sections.

2.1. Experimental setup

2.1.1. Product variety in the case study

In the experimental part of the study, five different products were assembled. These products were variants of LEGO cars, each built from an available set of LEGO bricks. The observed products are shown in Figure 1. LEGO sets provide a standardized and repeatable method to simulate the manual assembly of various products. Despite their simplicity, LEGO models accurately represent key features of assembly processes, such as following the assembly sequence and paying attention to detail, making them a suitable experimental framework for this type of research. In addition, LEGO brick sets are affordable, diverse, and readily available, which facilitates the simulation of assembling a variety of products.



Figure 1. *Product variants assembled at the workstation*

For analysis, the observed products were divided into work elements. A work element is the smallest logical part of work that can be performed independently. In the observed product family, 19 different work elements were identified. All observed products included some common work elements, as well as elements specific to each product. The precedence graph of the observed products is shown in Figure 2. In Figure 2, numbered circles represent work elements, and arrows indicate the order in which the work elements are assembled.

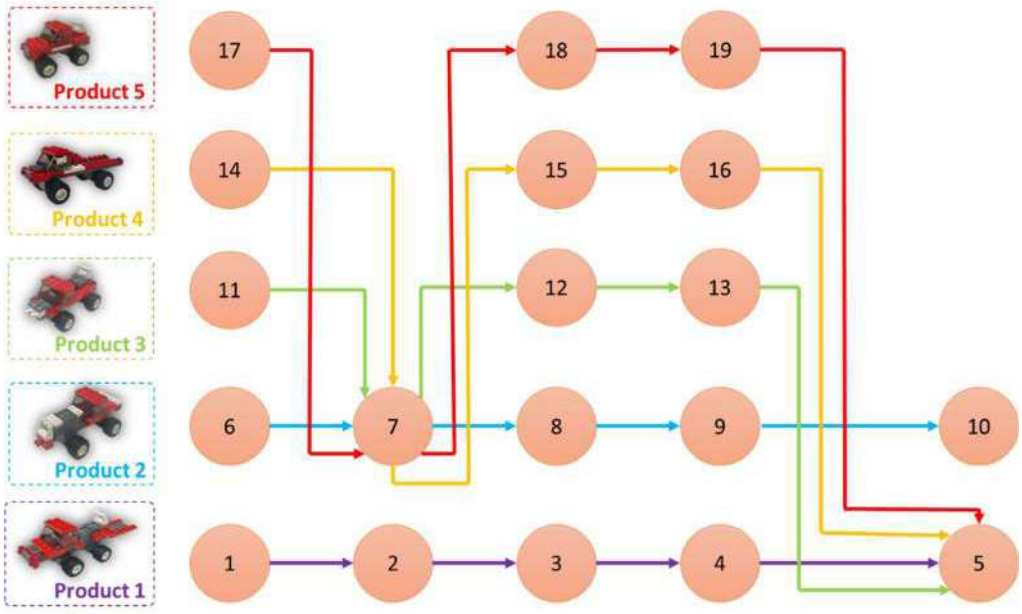


Figure 2. *Precedence diagrams for the considered product variants*

2.1.2. Workplace and Experimental Conditions

The experimental part of the research was conducted at a single workstation in a laboratory environment. As previously mentioned, the experiments involved two operators. The operator performing the assembly stood to allow greater mobility when retrieving parts. During assembly, the operator received digital instructions on a tablet, which were adapted to the sequence being performed at that time. The parts required for assembling the work elements were pre-organized and

sorted into boxes using the kitting method, ensuring that all necessary components were available at the workstation. Figure 3 shows an example of the arrangement of components at the workstation. The second operator acted as an observer, using a stopwatch to record the assembly time and performing quality control of the finished products after each experimental sequence was completed.



Figure 3. *Example of part arrangement at a workstation*

2.1.3. Experimental sequences

The experiments were conducted for seven predefined assembly sequences. The first five sequences involved the individual assembly of single products. In sequence 1 (S1), only one product was assembled consecutively, and the same applies to the next four sequences. The sixth (S6) and seventh (S7) sequences involved the assembly of three and five different products, respectively, following a predefined order. In each sequence, the product or the defined sequence of different products was assembled consecutively several times to enable a reliable assessment of the observed assembly times for the work elements. The assembly type and the defined order of product execution in each sequence are shown in Table 1.

Table 1. *Description of experimental sequences and assembly order*

Sequence	Assembly	Experimental sequences
S1-S5	Assembly of one product	-
S6	Assembly of three different products	2 x Product 3; Product 4; Product 5
S7	Assembly of five different products	Product 1; Product 2; 2 x Product 3; Product 4; Product 5

Before recording the results of the experimental sequences, the operator performing the assembly process was familiarized with the assembly instructions and completed several test assemblies to reduce the influence of learning on the assembly time measurements. The experimental sequences were executed consecutively from S1 to S7 over multiple days, with scheduled breaks between sessions to prevent physical and cognitive fatigue.

2.2. Key performance indicators and perceived workload assessment

During the experimental part of the study, objective performance indicators were monitored. These indicators enabled a quantitative, objective assessment of the manual assembly process and are explained in Section 2.2.1. In addition to the objective performance indicators, the study also monitored the perceived workload of the operators. The perceived workload is used as a subjective

indicator of the complexity of the assembly task. It was assessed using the NASA-TLX questionnaire described in Section 2.2.2.

2.2.1. Objective key performance indicators

Three objective indicators of success were monitored in the experiments:

- product assembly time,
- productivity, and
- number of defective products.

Product assembly time is the average time required to assemble a product at a workstation. It is measured as the sum of assembly process time and setup time. Setup time is the time an operator needs to identify a product variant, study the assembly instructions, and locate the selected parts required for assembly.

Productivity, as a quantitative indicator of success, is defined as the number of products assembled within a given period. The number of defective products refers to the total number of products that did not meet quality criteria during the observed assembly sequence, such as assembling the wrong component or incorrect rotation of an assembled part.

2.2.2. Assessment of perceived load using the NASA-TLX questionnaire

Perceived workload is defined as the subjective experience of the total mental, physical, and time effort an operator invests in performing a specific task. It includes how an individual perceives the complexity of a task relative to their abilities, available time, and working conditions. In the context of manual assembly, increased perceived workload can negatively affect performance, efficiency, and work quality, which may also be reflected in objective indicators of process success [6], [9], [10]. In this paper, perceived workload was assessed for each of the seven observed sequences by having the operator complete the NASA-TLX questionnaire after each sequence [11]. The NASA-TLX questionnaire is shown in Figure 4.

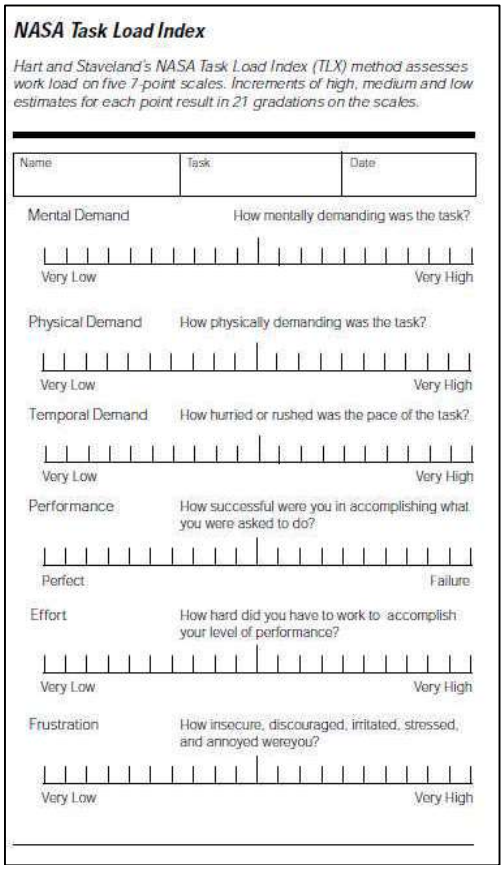


Figure 4. *NASA-TLX questionnaire [9]*

In the context of Industry 5.0, the NASA-TLX questionnaire is the most commonly used subjective tool for measuring operators' perceived workload [6], [7], It can be used to design operator-centered systems because it identifies tasks that cause mental workload and stress, which would otherwise remain invisible when using only objective performance measures. As shown in Figure 4, this tool collects data on operator's workload across six dimensions: mental demand, physical demand, temporal demand, performance, effort and frustration, with each dimension rated from 0 to 100 in five-point increments.

In this paper, the perceived workload of operators was quantified by calculating both unweighted and weighted workload indices. The unweighted score is the arithmetic mean of all six dimensions, with each dimension given equal weight in the final score. The weighted index reflects the relative importance of individual dimensions, recognizing that not all dimensions are equally important. Weights are obtained by pairwise comparison of dimensions, following the standard NASA-TLX method.

3. Experimental results and discussion

During the experiments using the NASA-TLX questionnaire for each sequence, results were collected for all six dimensions that assess the operators' perceived load. The results are shown in Table 2 and Figure 5.

Table 2. *The results of the assessment of the operator's perceived workload dimensions using the NASA-TLX questionnaire*

Sequence	Mental demand (4)	Physical demand (1)	Temporal demand (3)	Performance (0)	Effort (5)	Frustration (2)
S1	45	10	30	0	55	5
S2	35	10	30	0	45	5
S3	20	5	25	0	40	5
S4	30	10	45	5	55	10
S5	30	10	45	5	50	5
S6	65	40	60	0	85	45
S7	90	45	80	5	95	75

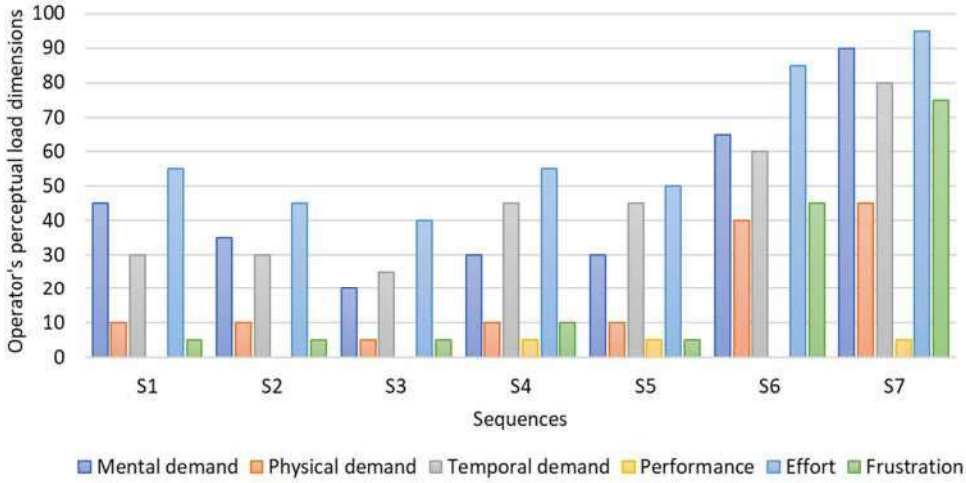


Figure 5. *The results of the assessment of the operator's perceived load dimensions using the NASA-TLX questionnaire*

In Table 2, the weight from the pairwise comparison of dimensions appears in brackets next to each dimension. The results in Table 2 and Figure 5 indicate an increasing workload trend for almost all dimensions from sequence S1 to S7. The findings show that increasing product variety in the assembly process leads to higher mental workload, greater effort, and increased frustration among operators. Assembling a single product result in a relatively stable and moderate physical workload, while assembling a larger number of diverse products causes a noticeable increase in physical workload. Despite the increased workload, the performance dimension remains at very low levels in all observed sequences, indicating that the operator completes tasks successfully even with a higher workload.
It is important to note that the range of values for the performance dimension is interpreted inversely compared to the other dimensions. To ensure that all dimensions have the same direction of workload interpretation – so that a higher value on the scale indicates a higher workload – the performance dimension is observed in reverse. In this case, a value of 0 indicates complete satisfaction of the operator with their own performance, while a value of 100 indicates great dissatisfaction with task performance.
The objective indicators of success collected in these experiments are shown in Table 3 as well as in Figures 6–8, along with the weighted and unweighted indices calculated, which represent the operator's perceived workload.

Table 3. *Objective indicators and perceived workload*

		Sequence						
		S1	S2	S3	S4	S5	S6	S7
Product assembly time [min:sek/pcs]		3:34	2:51	2:38	3:00	2:21	2:30	3:07
Number of defective products [pcs]		1	0	0	1	0	1	2
Productivity [pcs/h]		17	21	22	20	25	24	19
Total perceived workload of operator	Unweighted average	24.17	20.83	15.83	25.83	24.17	49.17	65
	Weighted average	37.67	31.67	24.67	37.33	35	66.33	84.67



Figure 6. *Perceived workload and product assembly time*

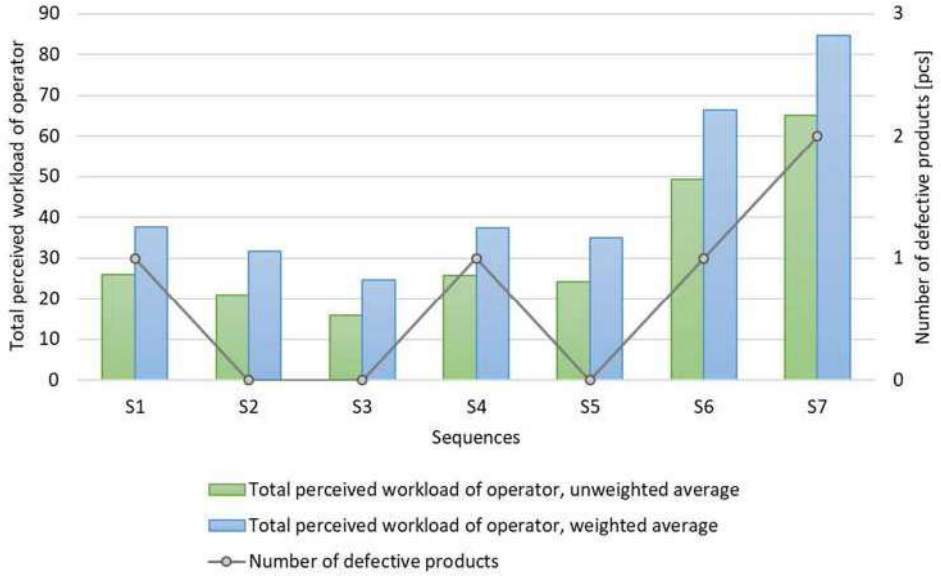


Figure 7. *Perceived workload and number of defective products*

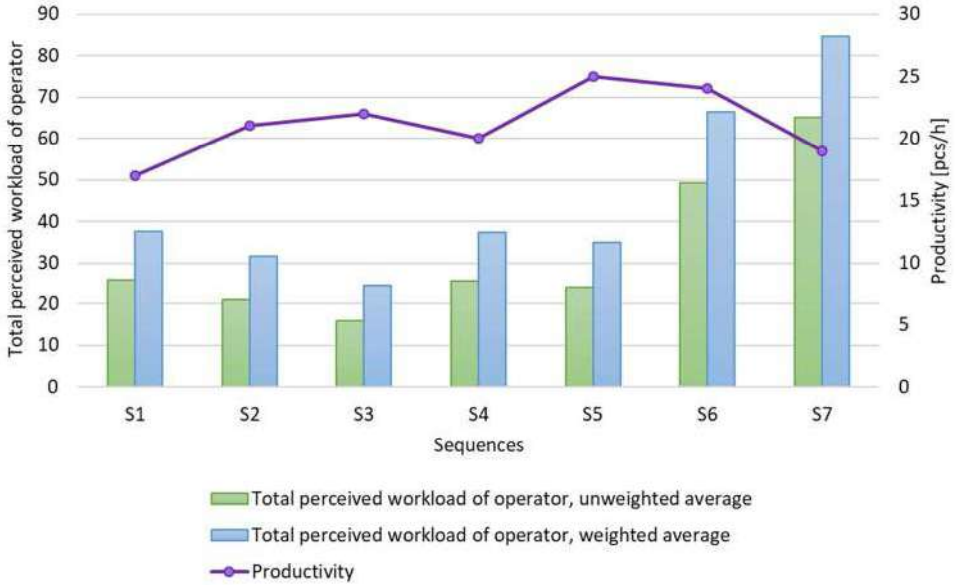


Figure 8. *Perceived workload and productivity*

According to the above presented results, an increase in perceived workload leads to decreased productivity and a longer average assembly time per product, while the number of defective products does not show significant changes between the observed sequences. The highest perceived workload values were recorded in Sequence 7, which was also the most demanding task due to the greatest product variety. The study results indicate that increased product variety significantly raises operator's perceived workload, with mental demand and effort playing dominant roles, while physical load remains relatively low.

Despite the increase in workload, the decrease in productivity is not proportional to the increase in perceived workload, indicating that operators can maintain a relatively high level of performance even with a higher cognitive load. For example, between sequences S5 and S7, there is a noticeable increase in weighted perceived workload (from approximately 35 to almost 85), while productivity decreases from 25 to 19 pcs/h, confirming that the increased workload does not result in a proportional decrease in efficiency. To further evaluate operator performance in mixed-product environments, the observed assembly times in mixed sequences were compared with product-mix-adjusted baseline values

derived from individual product sequences (S1–S5). For sequence S6, the expected baseline average assembly time was approximately 2:39 min/pcs, whereas the actual observed time was 2:30 min/pcs. This indicates that, despite the sharp increase in subjective workload and cognitive demand during mixed assembly, operator performance and task efficiency did not deteriorate. This outcome may be partly due to the nature of the experimental task. The assembly was based on LEGO components, which are visually distinguishable and easy to manipulate, and the assembly operations were limited to connecting elements without the use of additional tools or accessories. The increase in task complexity is therefore primarily reflected in cognitive demands, such as selecting appropriate parts and determining the assembly sequence, while the physical complexity of the task remains relatively low. The increased variety of products requires processing a larger amount of information and making decisions more frequently, which directly increases mental demand and, consequently, the effort invested and the level of frustration.

The changes in the dimensions used to evaluate the operator's workload are relatively moderate in the assembly sequences of individual products (S1–S5), while in the assembly sequences of diverse products (S6 and S7) there is a pronounced increase in effort, time requirements and, especially, frustration, particularly in sequence 7, which may indicate that the limit of the operator's cognitive capacity is being approached.

Furthermore, conducting the experiment on different days with rest periods effectively minimised cumulative fatigue. Although executing a fixed sequence (S1 to S7) could introduce learning effects, the marked increase in NASA-TLX workload in S6 and S7, despite growing task familiarity, indicates that product variety is the primary driver of cognitive load.

Comparison of the weighted and unweighted NASA-TLX results shows that both approaches follow the same general trend of increasing perceived load with increasing product variety. However, the weighted average highlights the importance of dominant dimensions such as mental demand, effort, and temporal demand, providing a more sensitive and realistic representation of changes in workload. This allows a more precise assessment of operators' perceived load in manual assembly conditions. In contrast, the unweighted average equalises the influence of all dimensions, which may lead to underestimation of the impact of critical load components.

4. Conclusion

This paper analyses the impact of product variety on operator's perceived workload, defined as subjective complexity in the manual assembly process. The results confirm the importance of including the human factor in the design of manual assembly systems, especially in the context of Industry 5.0. While increasing product diversity enhances production system flexibility, it also significantly increases operator perceived workload, particularly regarding mental demands, effort, and frustration. A comparison of the weighted and unweighted NASA-TLX indices shows that the weighted approach provides a more realistic representation of workload by highlighting the influence of key dimensions. From a practical perspective, the results indicate the need to optimize manual assembly systems by considering not only objective performance indicators, such as productivity, but also by balancing operator workload. This can be achieved by improving workplace design and work organization to reduce cognitive workload. The research was conducted in a controlled laboratory environment using a case study based on LEGO components. A methodological limitation of this study is that all experimental sequences were performed by a single operator to eliminate inter-subject variability, while a second participant acted strictly as an observer. Although this setup provided a controlled environment for exploratory analysis, it limits the generalizability of the absolute workload values to broader operator populations and real industrial systems. Therefore, future research should include a larger, more diverse sample of operators and more complex working conditions to validate these findings across different working styles and skill levels.

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