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Integrated lean and ergonomic assessment for the planning of human-centered factories

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Abstract

This research proposes an approach for evaluating human-centered work processes by combining Value Stream Mapping and ergonomic assessment of physical workload. Value Stream Mapping is a method used to create a visual representation of the flow of materials and information required to deliver a product, and aids in identifying potential bottlenecks and other constraints. However, it does not consider the effect of physical ergonomics on process execution and planning. To bridge this gap, the Ergonomic Assessment Worksheet screening tool is used to gain insight into unfavourable physical workload situations. The proposed approach follows five main steps: (i) scope definition, (ii) Value Stream Map, (iii) time study, (iv) ergonomic assessment, (v) combined analysis. A case study is conducted at a bicycle manufacturer to demonstrate the effectiveness of the approach in quantifying the impact of physical ergonomics on process performance. The method enables a systematic analysis of process chains to identify critical steps from both lean and ergonomic perspectives, emphasizing the importance of worker's physical well-being and the ability of ergonomic assessment methods to enhance Value Stream Maps.

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Keywords: human-centered factory; smart manufacturing; lean manufacturing; ergonomics; value stream mapping

1. Introduction

Industry 4.0 is shaping the industrial domain towards a high level of complexity and customization, also changing the profile and needs of the worker [1]. In this context, Lean Manufacturing principles and tools serve as a starting point for its technological implementation, enabling operations to be more flexible and efficient [2]. Value Stream Map (VSM) – part of the lean "toolbox" – is one of the main resources used in this journey. It helps to increase productivity by identifying wastes and making the entire process visible. Nevertheless, one of the limitations of VSM is that it is a process-centered tool, which does not incorporate aspects such as human factors and ergonomics into its analysis; as the focus on such aspects increases – driven by the need to meet society and workers' demand – established tools and methods must be able to work in a combined way.

Previous works have incorporated VSM with further modules such as quality, sustainability and life cycle assessment metrics [3,4,5]; however, case studies considering physical ergonomics within industrial scenarios are still underrepresented at the moment. Hence, by combining VSM with a screening tool based on the Ergonomic Assessment Worksheet (EAWS), this research proposes an integrated method for a human-centered assessment of assembly lines, taking into account manufacturing and physical ergonomic aspects. This is brought together in a case study at a bicycle factory, where the primary research question addresses the relationship between physical ergonomics and process efficiency; and how the proposed approach can contribute to the development of human-centered workplaces.

This paper is structured into five sections. Following the introduction, the technical background presents the state of the art referring to VSM and Human-Factors Ergonomics (HFE).

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In the third section, the research methodology is outlined. The fourth section presents the results from the case study, while section five provides a summary and outlook of the research.

2. Technical Background

This section presents the state of the art in VSM, HFE, and their combination, which forms the foundations for the methodology applied.

2.1. Value Stream Map

VSM is outlined in the book "Learning to See" as a tool that helps organizations visualize and understand the flow of materials and information in a process [6]. It allows businesses to eliminate, and prevent waste related to defects, unnecessary transportation, excess movement, waiting, overproduction, overprocessing, and excess inventory. This enables the creation of a map of the process highlighting opportunities for improvement by focusing on reducing or eliminating non-value-adding steps.

2.2. Human-Factors Ergonomics and assessment methods

Musculoskeletal disorders (MSDs) represent a major public health problem, affecting many industries and occupations. They are caused by exposure to repetitive motions, awkward postures, vibration, force exertion and other requirements related to the work environment [7,8]. Human factor ergonomics aims to tackle this problem by adopting a human-centric stance to achieve employee safety and well-being, and improve the performance of the system [9]. In this context, several methods for assessing physical load were proposed to analyze the ergonomic status of the workplace in the last decades. Table 1 summarizes the aspects related to some of the main assessment methods.

Table 1. Ergonomic assessment indices for manual assembly adapted from [10]

Aspect	NIOSH	OCRA	Strain index	RULA	REBA	EAWS
Posture		x	x	x	x	x
Upper limbs		x	x	x	x	x
Lower limbs				x	x	x
Load/Force	x		x	x	x	x
Frequency	x	x	x			x
Duration		x	x			x
Recovery		x				x

Generally, first and second-level tools are used for a quantitative ergonomic risk evaluation of a specific work sequence. First-level tools are risk-screening tools i.e. checklists; whereas second-level tools require a detailed analysis with index calculations derived from biomechanical analysis. In this research, we propose an adapted method based on the EAWS – explained in more detail in section 3. EAWS is a first-level screening tool – aligned with different international standards, including CEN and ISO – based on a three-zone rating system applied to obtain a quick assessment of the workplace, as shown in Figure 1. It consists of four sections for the evaluation of, respectively, working postures and movements with low additional physical efforts, action forces of the whole body or hand-finger system, manual material handling and repetitive loads of the upper limbs. An EAWS analysis may indicate that no further action is needed (green zone) or that redesign is necessary (red zone). In that case, an assessment based on a second-level tool must be executed for further analysis [7].

0-25 points	Green	No risk or low risk – recommended; No action is needed
>25-50 points	Yellow	Possible risk – not recommended; redesign if possible, otherwise take other measures to control the risk
>50 points	Red	High risk – to be avoided; Action to lower the risk is necessary

Fig. 1. EAWS traffic light risk assessment scheme

2.3. Value Stream Map and Ergonomics

Recent research by Rathore et al. [11] highlights a potential link between the implementation of lean principles in the manufacturing industry and a high prevalence of MSDs. The elimination of non-value-adding activities can increase ergonomic risk factors, as some may serve as a period of physical and mental recovery for the worker [12]. Hence, it is important to seamlessly integrate HFE with lean principles and tools to achieve a balanced and safe working environment in manufacturing. Against this background, Dominguez-Alfaro et al. [13] present the current state of research regarding the integration of VSM and ergonomics by reviewing 26 case studies. The majority (77%) of these studies focused on the healthcare sector, indicating the need for further research regarding industrial applications.

Given that, this paper introduces a combined approach incorporating VSM and an ergonomic screening method based on EAWS applied for assessing the process of a bicycle manufacturer. Using the current state map as a first-step diagnostic tool for further analysis, initial results help identify areas of improvement focusing on enhancing operations and reducing physical workload. Based on that, recommendations for starting continuous improvement steps can be derived.

3. Method

The proposed method follows five main steps as shown in Figure 2. Initially, to obtain a clear understating of the process, the definition of the scope provided the baseline for determining the value stream of the process according to the selected product family. In the following step, the VSM identified the flow of information from raw material to the final product according to customer demand. Considering the human-centered aspect of this research, the final assembly was selected for further analysis. The criteria used were the high value added to the final product, defined through VSM, and the intense manual labour observed. A time study was performed in step 3 to provide a basis for comparing the observed time with the reference process time.

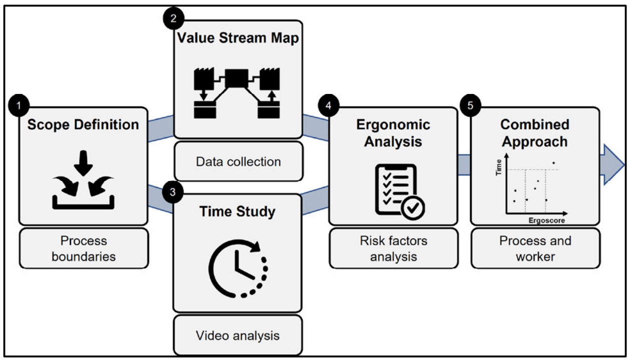

Fig. 2. Method applied

In the next phase, EAWS was used to measure posture and material handling; the overall ergonomic score was complemented by quantifying force exertion through the Moore-Garg observer scale. Because of the process's long cycle and non-repetitive nature, the ergonomic assessment was performed focusing on the tasks executed exclusively at the product. Finally, the last step proposes a combined approach where the ergonomic score, thresholds, and observed time indicate the system's overall state.

3.1. Selection of metrics & time study

The chosen assembly line was further assessed through the definition of the product family, and well-known lean metrics such as cycle time, takt time and lead time were evaluated. Additional metrics like operator performance and overall line performance were also considered [14]. Operator performance (OP) was used as a method for comparing the reference cycle time (CT) with respect to the observed cycle time (OCT), as shown in Equation (1):

$$OP = \frac{OCTi}{CTi} \times 100\% \quad (1)$$

Line performance (LP) represents the effectiveness of the assembly line by considering the overall reference cycle time (CT) with respect to the overall observed cycle time (OCT), as shown in Equation (2):

$$OP = \frac{\sum OCTi}{\sum CTi} \times 100\% \quad (2)$$

The process was recorded and a video time study – using ProTime Estimation – was performed to identify the utilization of resources, and measure inefficiencies. The sequential operations of each workstation were subdivided into smaller tasks and classified into value-added (VA), semi-value added (SVA), and non-value added (NVA), categorized as follows:

- Value-added: Directly contribute to the creation of the final product and can't be eliminated without affecting the product i.e. assembly of steering bar, fix saddle.
- Semi-value added: Does not directly contribute to the production of the final product but are still necessary i.e. quality control.
- Non-value added: Does not directly contribute to the production of the final product and can be eliminated without affecting the product. i.e. rework, unnecessary movement of people or materials.

The procedure followed a traditional lean approach and also considered aspects such as posture correction – as NVA task – to consider the effect of ergonomic design in the analysis.

3.2. Ergonomic analysis

The overall process was broken down into sequential parts and the EAWS checklist was used to assess postures and material handling in individual tasks. As the cycle times are longer than 5 minutes and the work is non-cyclic, static postures were rated as minutes per shift duration (spent in the position) and summed up with the asymmetrical score [7]. In the load section, manual material handling involves loads of more than 3-4 kilos and considers the postures involved in the working conditions as well as the frequency of handling. Finally, force exertion was quantified using a modified version of the Moore-Garg observer scale as proposed on the Threshold Limit Value for Hand Activity [15]. A weighted average of the individual tasks was used to calculate the final score for force exertion per workstation.

3.3. Combined approach

The ergonomic map of the assembly line along the observed cycle is the result of using the combined approach of the proposed method. It is divided into four main quadrants where the upper limit is defined by the takt-time of the process; workstations within this zone are identified as bottlenecks in the overall process; the HFE risk assessment area is divided into a three-zone rating area following the EAWS representation system. The visualization map helps to identify and prioritize workplaces flagged as critical from a production and ergonomic standpoint.

4. Case Study

The company produces 23 different products – customizable bicycles. The case outlined in this section focuses on one specific product family, which represents 15% of total production output.

4.1. Process Description

The process runs 5 days per week and weekly production orders are sent to the shop floor composed of 5 major steps, as seen in Figure 3.

Fig. 3. Process flow

Product demand is forecasted on an annual basis and adjusted every 2 months according to market variations. Furthermore, orders are batched by product configuration on the shop floor to reduce changeover times.

4.2. Value Stream Map - Current state analysis

The VSM was drawn based on the observation of the process described in the previous section. It represents the current situation of the process divided into operations, indicating the process flow, requirements and the stream of customer information to the supplier as shown in Figure 4.

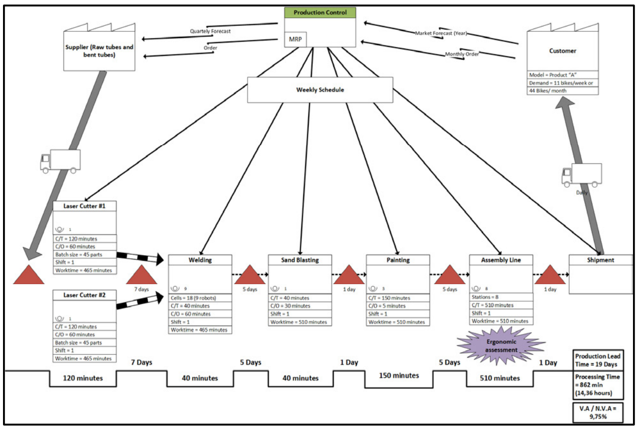

Fig. 4. Value Stream Map representation for the case study.

The process is make-to-stock until welding, where it is kept within the threshold of the safety stock. It follows a production strategy based on the scheduled forecasted demand. Once it reaches sandblasting, the process is pulled following a make-to-order approach, where the frames are sent downstream according to the weekly production order.

The first process block, laser cutting, is divided between two machines working in parallel. One week before the production order is issued to the welding, raw parts (frame tubes) are cut as per requirement. Next, the parts are sent to the welding area which is composed of 18 cells. For the assessed product family, the frame undergoes both automated and manual welding with an average cycle time of 40 minutes. As the process moves downstream, 1 worker operates the sandblaster with a 40-minute cycle time, preparing the material's surface for the next step. After that, the frames are sent to the paint shop, which is a 3 steps automated process with a cycle time of 150 minutes and operated by 3 workers. Moreover, orders are batched by frame type and colour to avoid setup time constraints. Finally, after reaching the assembly line, the frame is assembled along 8 workstations with 510 minutes of overall cycle time through a continuous flow. It is followed by an inspection process, and if approved, the product is prepared for shipping, which occurs daily.

Data blocks show cycle time (CT), which is the time needed for each process to be completed. The time ladder at the bottom of the map represents the overall time it takes to complete one product. As a result of adding all intermediate lead times, the Production Lead Time (PLT) is obtained, while the Processing Time (PT) is derived through the addition of all cycle times. The efficiency of the cycle can be determined by dividing PT by PLT, resulting in 9,75% at the current state.

4.3. Assembly line analysis

According to the current state map, the assembly line accounts for 60% of the overall processing time of the product. Besides, it is the only area where the work is entirely manual. For those reasons, it was ergonomically assessed and a time study was performed to compare the observed process with the reference time and quantify existing non-value-added steps.

It was observed that 5 of the operators performed on average 39,4% faster when compared to the reference cycle time, achieving the peak of 53,11% on workstation 4 as seen in Table 2. Conversely, workstations 1, 2 and 7 exceeded the reference cycle time, with workstation 1 being the bottleneck of the process for breaching the current takt time of 80 minutes.

Table 2. Performance per workstation.

Workstation	Number of operations	Observed C/T (min)	Reference C/T (min)	Performance (%)
1	4 operations	83,22	49,50	-68,12%
2	5 operations	51,33	38,48	-33,39%
3	5 operations	30,85	41,08	+24,9%
4	7 operations	18,42	39,35	+53,11%
5	5 operations	20,77	41,27	+49,67%
6	4 operations	29,89	57,10	+47,65%
7	10 operations	51,31	43,12	-18,9%
8	6 operations	30,70	39,20	+21,68%

From a production point of view, the current performance of the line (9,34% better than reference time) is capable of meeting market demand; however, preliminary results indicate potential line balance problems with the allocated tasks not being evenly distributed from an ergonomic point of view.

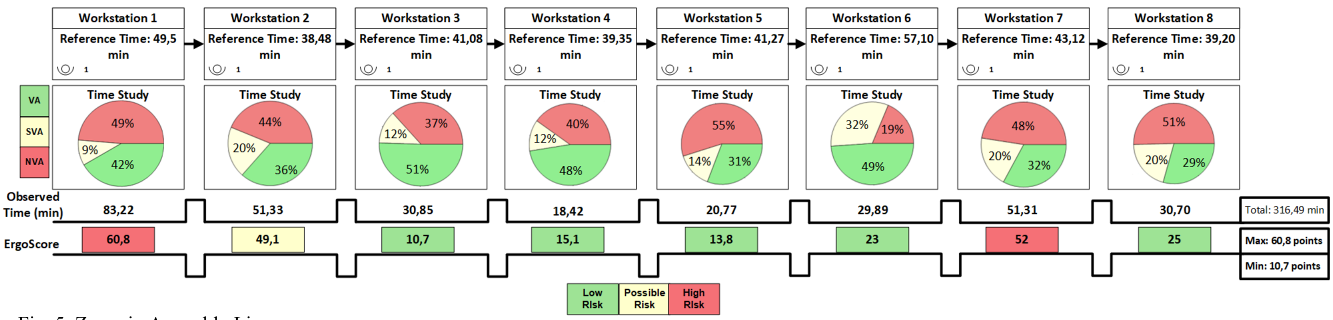

Fig. 5. Zoom in Assembly Line

Through assessing the individual operations of each workstation, shown in Figure 5 it is observed that the most physically demanding activities – with higher ergonomic scores – are distributed among the worst-performing workplaces, which are workstations 1,2 and 7. It matches the overall ergonomic assessment results, which rank them either as yellow or red zones, thus providing insight into the current workplace design, possible areas for improvement and system performance.

As a result of the time study, it was identified that around 43% of the work at the assembly line is non-value added from a lean perspective. The following forms of waste represented around 80% of the non-value-adding activities:

- High rates of waste related to movement (i.e. walking to grab tools and parts) were observed across all workstations, being the most prevalent form of non-adding value activity, accounting for 50% of the category.
- Rework activities represent 14,5%. Time spent fixing previous steps due to quality issues.
- Posture adjustment is equivalent to 11%. Time spent when workers had to stop the operation and fix their posture due to executing a task in an awkward posture.

From the manufacturing planning point of view, reducing the non-adding value activities is necessary to improve the system's efficiency. The high percentage related to "posture adjustment" is one of the indicators regarding the overall design of the workplace, and can be used as a starting point for a more holistic ergonomic analysis aiming at improving both efficiency and work conditions.

4.4. Ergonomic analysis

Table 3 outlines the partial ergonomic result regarding the workstations ranked within the orange and red zones.

Table 3. Ergonomic score of the workstations within the orange and red zones

Parameter	Workstation 1	Workstation 2	Workstation 7
Symmetric (posture)	13,5	11,6	6,9
Asymmetric (posture)	40	34	40
Material Handling	5,7	1,5	3,9
Force Exertion	1,6	2	1,2
Ergonomic score (total)	60,8	49,1	52

The resulting values of asymmetric postures reached the limit of 40 points in the EAWS posture scale at workstations 1 and 7; associated with trunk flexion, lateral bending and far reach, there is evidence in the literature that such asymmetric postures elements are risk factors for back pain and can contribute to the development of MSDs [16,17]. Considering the work's long cycle and non-repetitive nature at the assembly line, the obtained score for symmetric postures was noticeably low. Long-cyclic tasks can lead to longer waiting times and longer postures in less strenuous body positions, meaning that recuperation effects are possible, which is not taken into account in short-cyclic tasks [18]. However, while a particular posture may be symmetrical, it may still be awkward or uncomfortable for the worker as shown in Table 4.

Table 4. Observed symmetric postures

Operator	Result	Observation
1	21% of the working time "standing bent forward between 20-60 degrees".	Over an extended period of time can cause discomfort and strain on the back muscles, leading to poor posture thus contributing to back pain [19].
2	18% of the working time "standing bent forward between 20-60 degrees" and "standing upright with the elbow above/at shoulder level".	Over time, it can cause discomfort in the neck and shoulders due to strain on the shoulder and upper back [20].
7	25% of the working time "standing".	Standing for prolonged periods of time without regular breaks can lead to fatigue and discomfort [21].

Overall, the assembly line is characterized by its low physical workload due to the handled loads throughout the process – quantified by the material handling score. The workbench used for supporting the product during assembly is the main heavy component handled – above 4 kilos; it is repositioned by the operator at the start and end of the process and then pushed to the next station. Considering the low rolling resistance of the workbench, frequency and the position of the operator, the effort required is perceived as negligible. On the other hand, it was observed that force exertion per task was not evenly distributed, achieving peak loads during specific stages intercalated with less demanding steps.

4.5. Overall analysis

Figure 6 shows the process considering the overall ergonomic map along the product cycle. As observed, the workstations with higher ergonomic scores were more physically demanding due to tasks associated with the assembly of large sub-components; the workstations within the green zone are in the majority characterized by precision work i.e. wiring, and electronics; in all workstations, despite the level of intensity, awkward postures was the main contributing factor to the final score.

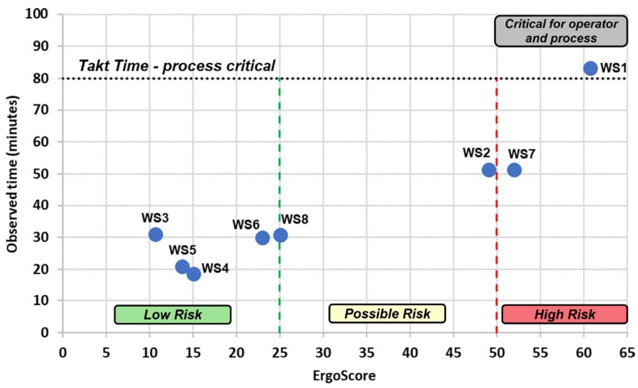

Fig. 6. Ergonomic map of the assembly line along the observed cycle.

The workbench was diagnosed as the root cause of this factor. It restrains the operator's access to certain areas of the product, thus amplifying the effect of unfavourable positions at the workstations with higher physical demands – especially in terms of asymmetric postures i.e. lateral bending and trunk flexion. In order to evenly distribute the ergonomic workload, a re-balance of the line combined with a job rotation strategy can improve the overall efficiency of the system [22]. As outlined in section 4.3, wastes related to unnecessary movements such as walking to grab tools and parts were assessed. By systematically applying 5S, tools and parts can be set in order in a logical and easy-to-access location, reducing the time it takes to locate and find them.

5. Summary and Outlook

The combination of VSM and ergonomic assessment described in this paper shows that ergonomic and production factors can provide insights for the improvement and development of human-centered workplaces. As part of the proposed method, constraints related to process design and ergonomic elements are identified to assess the workplace holistically and optimize its future state. For validation purposes, the feasibility and outcomes of its application were evaluated and tested in the production process of a bicycle manufacturer.

However, the scope of the analysis can be extended based on further data capture, thus allowing the identification of more factors that can impact manufacturing and ergonomic aspects. Also, the ergonomic map presented in Figure 6 indicates an influence of the time factor over the final ergonomic score. Further work will focus on the development of an automated assessment system integrated with a digital VSM model for continuous evaluation of the workplace; this will assist in determining the ergonomic potential of individual tasks based on the workload level. Additionally, cognitive aspects will be taken into account in order to increase robustness from a human-centered perspective.

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