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Article

Application of Collaborative Robots for Increasing Productivity in an Eyeglasses Lenses Manufacturer

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Abstract. This research focuses on a framework for making decisions when adopting collaborative robots (cobots) to collaborate with or replace human workers. Top management at a real-life case study firm that manufactures a variety of eyeglasses lenses wants to implement cobots in the sorting process since such a repetitive task has been shown to have a significant negative influence on workers' ergonomic ailments. Its current procurement decision-making process focuses solely on financial perspectives without taking into account any other significant criteria. Therefore, the purpose of this study is to investigate the elements that are crucial in deciding whether to use cobots in manufacturing lines., Multivariate statistical methods, comprising the exploratory factor analysis (EFA) and confirmatory factor analysis (CFA), are applied to analyse the elements that are associated with the latent variables such as safety, ergonomics, productivity, quality, system, internal organisation and external organisation. In addition, alternative deployments of cobots in the case study are validated through the ARENA simulation software. More specifically, the results showed that using cobots in the workplace might boost output while lowering WIP, waiting times, the number of tasks in queue, and the workforce. In addition, cobots may reduce employee ergonomic risk and enhance workplace safety.

Keywords: Cobot, eyeglasses lenses, productivity improvement, factor analysis, simulation.

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1. Introduction

Colgate and Peshkin introduced the notion of collaborating robots (cobots) in 1996 [1]. Cobots are devices which enable direct physical interaction between humans and robots under the command of a computer program system. Most cobots have an arm-like form akin to conventional robots [2]. Cobots can work closely and safely on a table beside humans in the same workspace; however, they are smaller and lighter than the conventional robot arm [3]. When humans or foreign objects approach their work zones, cobots are designed to make use of the most sophisticated sensors to securely avoid their motions to prevent humans from accidents, for example, by slowing down or stopping [4].

Due to their high level of safety and ability to collaborate with humans, cobots are being employed more frequently in the industrial sector [5]. Industry benefits from the employment of cobots in numerous ways, especially through greater effectiveness and reduced production costs [5]. Cobots assist workers in performing dangerous or potentially harmful tasks and lessen their physical workload while carrying out laborious tasks, such as picking and placing parts, feeding workpieces, lifting heavy parts, and transporting parts, which demand repetitive work and may be harmful to their health [6]. Additionally, cobots have the ability to carry out complicated tasks that are unlikely to be completed by workers manually [7]. Cobots can collaborate with humans as members of a team, which could yield greater work outcomes in terms of quantity and cost [8]. Moreover, cobots are more flexible, easier to install and program, and take up less space than conventional industrial robots [9, 10].

The case study factory where this research is being conducted manufactures a wide variety of eyeglass lenses. Given that it is done manually and mistakes commonly occur when new or temporary employees begin their duties, the sorting process of the packing line is investigated in this study. Sorting involves determining whether workpieces require human or automatic packing as the initial step in the packaging process. The decision to sort is made manually. To solve the problem, the supervisor of the process needs to assess whether it is advantageous and practical to switch over to cobots in place of human labour. However, the current decision-making criteria solely take into account financial considerations and ignore additional essential factors.

To take a more comprehensive approach, this study investigates the more variables that could influence the conversion of such a manual process into an automated or hybrid process in which a robot (cobot) and a human being collaborate on their work. Hence, additional pertinent factors are taken into account in addition to the cost-effectiveness criteria, such as productivity, quality, labour substitution, safety, ergonomics, and project profitability. The ultimate goal of this research is to offer a framework for making decisions regarding the deployment of cobots to collaborate with or replace human workers.

Following is how the remaining sections are arranged. In Section 2, a review of relevant literature is done. Section 3 presents the problem definition. In Section 4, the research technique is described. Section 5 presents the experimental findings. Finally, Section 6 summarises the findings and suggests additional research.

2. Literature Survey

2.1. Cobots

Historically, the performance of robots has been continually improving with the growth of technology and innovation. Many industries introduced robots to corporate operations to acquire an edge over their competitors. The deployment of robots in the manufacturing process has been constantly enhanced, particularly the capacity to communicate between humans and robots as well as between robots and machinery. Furthermore, the advancement of robot learning abilities is accelerating, leading to higher-functioning robots being in greater use trends.

In the past, robots were large, heavy, and expensive. However, today's robots are designed to be smaller, lighter, and cheaper. Moreover, people can also operate them closely. To survive in a swift technology-changing era, many companies decided to replace human workers with robots for cost savings and let robots play a greater role in the industry, especially in industries that employ a large number of workers or are unable to hire skilled workers. Replacing humans with robots helps reduce labour costs which can help entrepreneurs with current higher wages and a shortage of working-age workers [1].

At the present time, advancements in robot technology allow for the integration of robots into human workspaces. This leads to increased production, less fatigue from repeated operations, and decreased complexity of jobs or accidents done by human workers [2]. Cobots are collaborative robots that share the same workplace with human workers [3]. The primary distinction between cobots and typical industrial robots is that cobots do not require workers to engage with them while they are in a secure environment or at a safe distance. When encountering impediments, cobots activate a sensing system that allows them to move more slowly than industrial robots that do not have this mechanism. Cobots have a shorter setup time than typical robots. Cobots are useful in the automation of workstations and can be utilised for tasks such as picking up parts, welding, assembling, or inspecting workpieces [4].

The International Federation of Robots (IFR) defined the level of collaboration between robots and human employees into five categories, which are as follows:

1. Cell: Robots and workers operate independently without cooperation space and safety fence (Fig. 1).

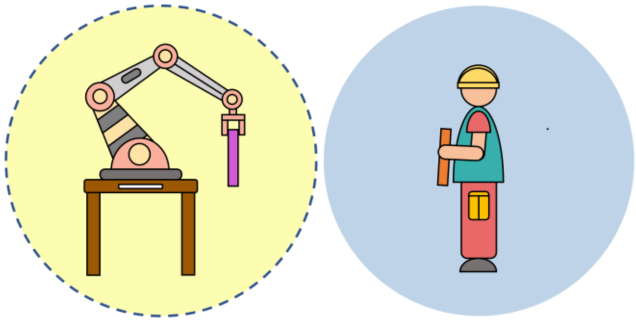

Fig. 1. Cell collaboration.

2. Co-existence: Robots and workers operate independently without collaboration space and a safety fence (Fig. 2).

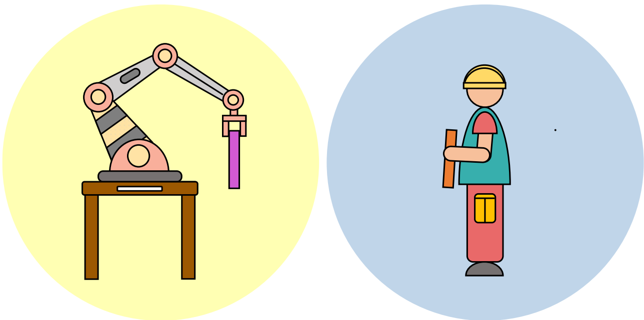

Fig. 2. Co-existence collaboration.

3. Sequential: Robots and human workers share the same workspace and conduct their responsibilities consecutively on the same piece at various timeslots (Fig. 3).

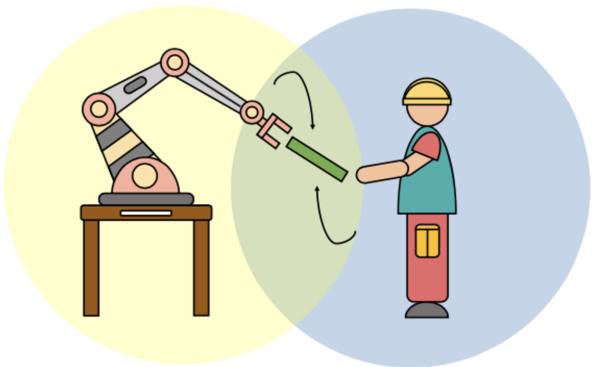

Fig. 3. Sequential collaboration.

4. Collaboration: Both robots and humans operate on the same task at the same time (Fig. 4).

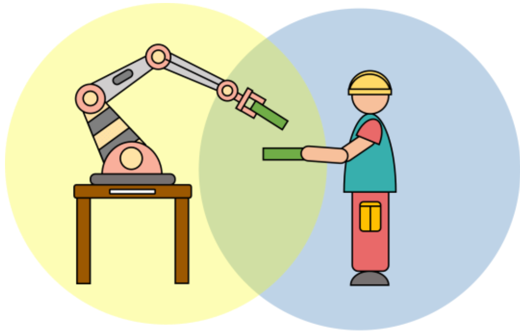

Fig. 4. Collaboration and responsive collaboration.

5. Responsive: Robots react in real-time to human worker movement (Fig. 5).

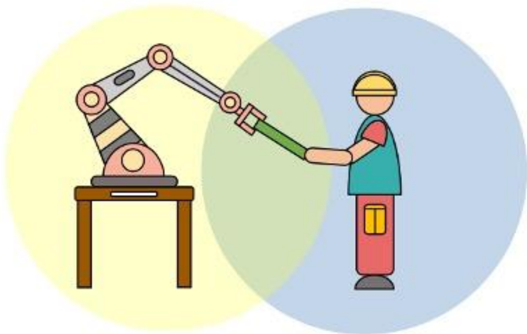

Fig. 5. Responsive collaboration.

Recent reviews of the applications of typical robots and cobots in assembly operations were described by Chutima ([26], [27], [28], [29], [30], [31] and [32]).

2.2. Ergonomics

According to the International Labour Organisation (ILO), ergonomics motivates the academic discipline of human biology and engineering applied to workers and working environments to ensure employee satisfaction and maximal productivity. As a consequence, ergonomics is a discipline concerned with enhancing job performance to better fit the physical and mental capabilities of workers. Hence, the study of the conditions at work that link workers and the working environment is known as ergonomics. In addition, this subject matter helps evaluate if the workplace's design or improvement is appropriate, prevents dangers that might jeopardise workplace safety and health, and offers an acceptable working environment for workers. Ergonomics experts or ergonomists are those who study the relationship between workers, the workplace and work design [5].

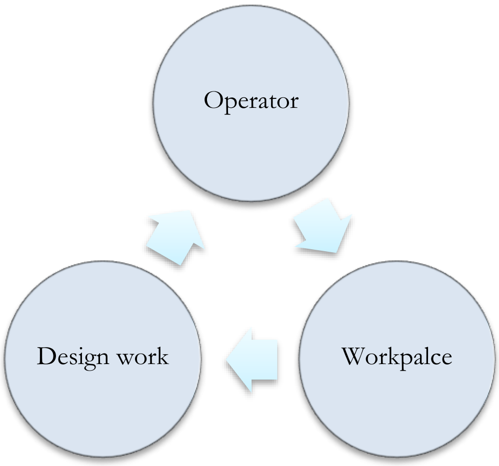

Fig. 6. Ergonomic relationship [6].

In today's industry, manual work remains integral in the manufacturing processes. Long hours of manual labour, poor working postures, and inadequate working conditions will cause fatigue, resulting in detrimental work. The human body should be loaded as lightly as possible to avoid fatigue and work-related injuries. Using ergonomics at work, such as examining postures at work or reviewing working environments to enhance employee postures and motions, are beneficial for tool design, machine design, and office desk chair design. The following is the benefits of ergonomics [7, 33].

- Improve safety for workers and occupational health.
- Boost employee motivation at work.
- Improve the overall quality of work.
- Improve the work system's efficiency and productivity.
- Enhance the possibility for the formation of trade competitiveness.
- Lower the rate of worker departure and resignation.
- Reduce work-related injuries and health concerns.
- Lower the establishment's staff costs.

While deploying the workforce, it is vital to examine the workplace conditions to assess the risks of working posture to modify working posture, adapt to the working environment, or decide to utilise robots in place of workers. There are various ergonomic approaches for measuring postural. The most prevalent methods for assessing include RULA [8], REBA [9], OCRA [10] and NIOSH [11].

2.3. Productivity

Takt time and cycle time are two essential metrics for assessing manufacturing operations' productivity, and they are regularly set as targets for productivity improvement. The system performance could be made more productive by lowering cycle times, lead times and takt times.

2.3.1. Takt time

"Takt" is a German term meaning "rhythm" in music. The execution of the guideline is compatible with the name's definition in that operators plan the manufacturing of each product according to the given target or time frame (i.e. takt time). Takt Time may be used to determine the manufacturing time of each product based on the demands of the consumers, which might take seconds, minutes, hours, or weeks. Employees must regulate the pace of outputs in each production station within the takt time constraint to decrease production risks while successfully meeting targets [13]. The takt time can be modified to meet market demands and produce with greater efficiency by incorporating cobots into the production process and allowing cobots to work for a certain time that corresponds to the needs of the customer. Make production possible efficiently and reduce the occurrence of over or underproduction according to market demand.

2.3.2. Cycle time

Cycle time is the amount of time it takes for every single component of a production line to be finished. In most cases, the production cycle time is dependent on the rate of production, or in other words, the completion time of each workpiece is equal to the most time-consuming station time. The station that consumes the most time in the line is named a bottleneck station. Workpieces in the workstations that take less time to process than takt time have to wait until takt time is completed [14]. In general, integrating cobots in operations with workers can save working time, and using cobots at the bottleneck station can result in a shorter production cycle time.

2.4. Project Analysis

The approach of maximising the utilisation of resources within the constraints of objectives or restricted resources is referred to as project analysis. Project analysis is a method used to assess a project's success which must be examined from the planning stage until the project completion stage. When examining a project, the analyst should be aware of the project's expenses and profitability. This aids in estimating expenditures and earnings during the project's duration. Project analysis may be done in a variety of methods, including cost analysis. The objectives and goals of any project analysis also involve the project's returns and impacts (e.g. economic, social, cultural, and environmental). A financial feasibility analysis needs to be conducted to prioritise investment decisions. Financial tools are essential to aid in analysis to make proper and efficient investment decisions. In doing that, the future cash flow projection is generated, and then the financial indexes are calculated using the following methods, i.e. Benefit-Cost Ratio (B/C Ratio), Payback Period (PB), Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (B/C Ratio) [15].

2.5. Related Literature

Malik and Bilberg [16] presented a framework for dynamic job distribution in an assembly line that is based on worksite components and co-working spaces. The experts who participated in the study separated the criteria and evaluated them based on their personal experiences. There are several primary criteria and sub-criteria, such as the main criterion of safety, sub-criteria consideration of workpieces that pose safety hazards (e.g. sharp edges, pointed edges), and the danger of head and neck accidents. However, the parameters used for separating them do not address how cobots are chosen. Only in part on how they function were the criteria specified.

According to Gjeldum et al. [17], a task assignment approach that includes the criteria for robot-human interaction and the bounds of each criterion is offered, with experts providing the criteria based on their expertise. In the actions section, several criteria were defined, e.g. decreasing worker exhaustion, decreasing the number of workers, reducing the work area, reducing production time at a bottleneck workstation, and so on. However, the characteristics they shared did not address how the decision for cobots was reached. Only in the operation section were the criteria given. Moreover, the criteria were not classified into major and sub-categories resulting in individual decisions that might lead to biased criteria.

Ranz et al. [18] presented a heuristic procedure of morphological analysis to create a model that can be used as a framework to increase the value of robot-human interaction and symbolise the complexity of human-robot collaboration implementation through multidimensional structures. The criteria were classified into conceptual and technical components, as well as quantitative and qualitative aspects of human-robot collaboration (HRC) implementation. Several criteria were listed under the key criteria in the measurement section. There were five basic criteria and sub-criteria, including finance, workpiece qualities, processes, systems, and safety. However, the qualities they shared did not address how cobots were chosen. Only in the operation section were the criteria given.

Cohen et al. [3] reviewed the research and proposed a methodology to examine the basics and make decisions regarding where and when to deploy cobots simply. The criteria described the characteristics of cobots, such as robot pricing issues, the weight of the cobot, the number of axes, the programme, and so on. However, the criteria they shared did not address how decisions concerning the usage of cobots were made. Only in the section on operation were the criteria specified.

The study provided by Correia Simes et al. [19] identified and described the elements impacting managers' propensity to deploy collaborative robots or cobots in manufacturing. The criteria from the investigation were obtained from three theories, including (1) Diffusion of Innovation (DoI), (2) Technology-Organisation-Environment (TOE), and (3) Institutional Theory (INT). Sub-criteria and primary criterion are separated. The essential criterion was the technology both inside and outside the firm. However, there were no operation-related requirements.

Simes et al. [12] proposed a paradigm for representing the degree of complexity of influencing elements in the context of human-robot interaction. This framework was created for content analysis. The guidelines and recommendations of the publications examined were divided into three categories. In Category (1), human performance and technological elements were determined. Category (2) was based on human performance teams' performance. Category 3 was an integrated method of designing robot-human collaboration. However, the qualities they shared did not address how cobots were chosen.

According to Papetti et al. [21], a collaborative design had to balance safety, ergonomics, efficiency, and adaptability. There was a primary criterion and sub-criteria; nevertheless, the split criterion excludes cobot decision-making.

Berx et al. [21] defined major and sub-criteria for human-robot collaboration from a broader and more complete perspective than technological concerns. The primary criteria and sub-criteria were separated. People, Technology, Collaborative Space, Organisation, and External were the five main requirements. The criteria mentioned include how to choose which cobots to employ, but not all of the essential criteria, including the primary criterion, i.e. people, sub-criteria, and physical ergonomics. Only work-related fatigue was evaluated.

The decision-making criteria for the usage of collaborative robots were separated into two primary areas based on a survey of relevant literature:

1. Operation: criteria connected to operations or objects related to the practical implementation of ideas or procedures. The primary operational criteria are as follows: safety, ergonomics, productivity, quality, and system.

2. Non-Operation: is a non-operational criterion that may be separated into two categories, i.e. internal organisation and external organisation.

This two-theme criterion encompasses the factors involved in selecting a collaborative robot, taking into account the criteria division presented in Table 1. It is clear that the scope of this work is far greater than that of earlier research.

Table 1. Summary of the cobot implementation survey.

Article author	Operation					Non-Operation	
	Safety	**Ergonomic**	**Productivity**	**Quality**	**System**	**Internal Organisation**	**External Organisation**
Malik & Bilberg [16]	✓		✓				
Gjeldum et al. [17]		✓	✓	✓			
Ranz et al. [18]	✓		✓		✓		
Cohen et al. [3]					✓		
Correia Simões et al. [19]					✓	✓	✓
Simões et al. [12]	✓	✓			✓		
Papetti et al. [20]		✓	✓	✓	✓		
Berx et al. [21]	✓	✓			✓	✓	✓
This article	✓	✓	✓	✓	✓	✓	✓

2.6. Factor Analysis

Factor analysis is a technique for minimising the number of variables [22]. By grouping or merging variables with comparable qualities, the factors must be smaller than the original variables. A factor analysis is a thorough summary of various variables that have been observed [23]. It is often referred to as a strategy for reducing the number of variables. The factor analysis approach examines the observed variables' correlation structure and groups the related variables together. There are two types of factor analysis techniques: exploratory factor analysis (EFA) and confirmatory factor analysis (CFA). Factor analysis has the advantage of assisting in determining the factor of several variables without the requirement to rationally establish which variable is independent or dependent. It further aids in the resolution of regression analysis difficulties involving highly correlated independent variables or multicollinearity [22].

2.6.1. Exploratory factor analysis (EFA)

The exploration of the link between variables that have been observed without prior knowledge of that relationship is known as exploratory factor analysis. As a consequence, we want to know whether the variables are linked and belong to the same factor. In addition, it could be explained if uncorrelated variables could minimise the number of variables; or if any variables should be included in the same factor. Exploratory factor analysis is commonly used to investigate the variable structure, minimise the number of variables, and validate or disprove ideas [23, 24].

2.6.2. Confirmatory factor analysis (CFA)

Confirmatory factor analysis is the evaluation of the relationship between variables that have been discovered after being made aware of one. It may relate to relevant instructions or analysis of relevant research publications. As a result, it is critical to develop a model that depicts the variable interaction. As a consequence, after determining the number of components, the approach will be utilised to assess whether or not the correlation model is as predicted [23].

3. Problem Definition

One of the largest manufacturers of numerous kinds of eyeglass lenses is the case study company. This study examines the sorting operation since it is a labour-intensive step that needs human labour and is a step in the packaging line. Figure 7 depicts the packing line's process flow. The factory has to pay more for additional hires or temporary workers to handle the increased production volume. Additionally, the production statistics show that these new employees frequently have lower productivity rates and are more likely to create errors. To replace human labour, the manager has to study if the integration of cobots into the process is feasible.

The sorting station receives the work when it enters the packaging process. This process separates the work into automatic and manual packaging. As soon as the job has been divided, it will be transmitted to the stamp workstation. If the project involves automatic packaging, it will be divided to determine which equipment will be used for the stamping. If packaging is to be done manually, however, packing envelopes and labels will be made before stamping types are divided according to each machine. After the automated packing has been stamped, it is brought to a station for inspection. At this station, the workpiece will be examined to check for flaws and the accuracy of the stamping on the workpiece. When everything has passed inspection, it is taken to the kitting station and placed in an automatic packaging machine. The following station receives the completed stamp for the hand packaging procedure. Both the workpiece inspection and packaging are done at the same station. The job gets sent to the workstation, the last station, once it has been finished at the station. A card and a certificate of product quality guarantee are added to the bundled workpiece using the kitting process. The whole process is illustrated in Fig. 7.

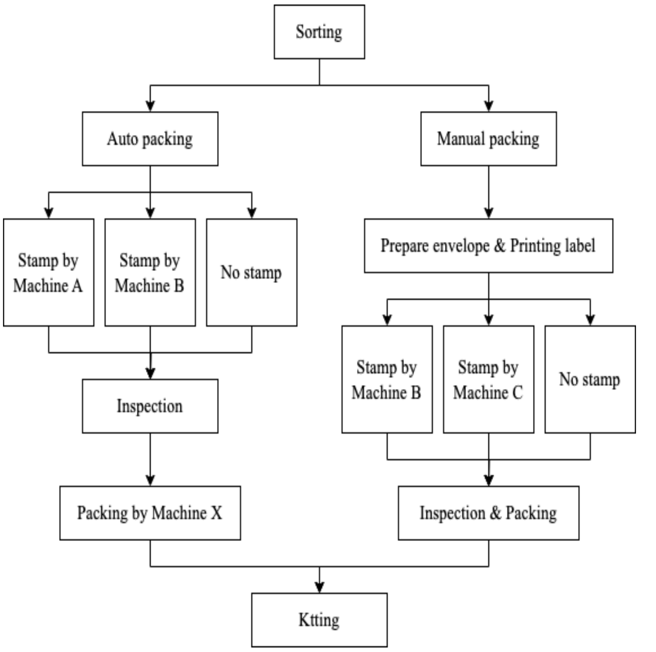

Fig. 7. Process flow of the packing line.

The manufacturer intends to reduce sorting errors and workers' wages that are only evaluated on a financial basis by integrating cobots into the sorting operation. Other factors, such as increased productivity, safety, and ergonomics, are not taken into account in the decision-making process of the manufacturer at present. The manager additionally encounters a challenge because there are no instructions for using cobots to replace workers in the operations manual of the company in question. This project, which intends to study what factors need to be taken into account when the cobots are needed to be deployed in the facility, is started as a result.

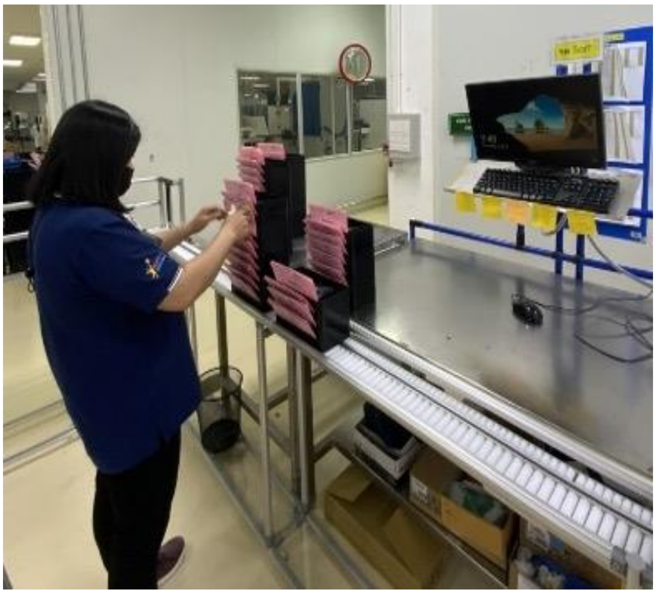

Fig. 8. Sorting operations performed by a worker.

4. Method

This study plans to examine the variables affecting decisions regarding employing cobots at work. First, the general condition of the plant's operation is examined. Next, information is gathered regarding the decision to introduce cobots. To ascertain the significance of each aspect, a survey of experts is carried out. To reach a conclusion, two methods—factor analysis and computer simulation—are used, as shown in Sections 4.1 and 4.2, respectively.

4.1. Factor Analysis

This section's goal is to present a framework for making decisions on the usage of cobots to supplement or replace human labour. It employs a qualitative research methodology. The questionnaire for the factor analysis in this study has 41 questions. The formula for calculating group size using the minimal number of responders is N = Question Items + 1.

In the factory which produces lenses, the participants in the survey were 42 cobot experts. Surveys and in-depth interviews were employed to collect relevant data. When using factor analysis, the intent was to create as few variables as possible. In other words, similar variables may be clustered, aggregated, or integrated into one category using the statistical technique of factor analysis.

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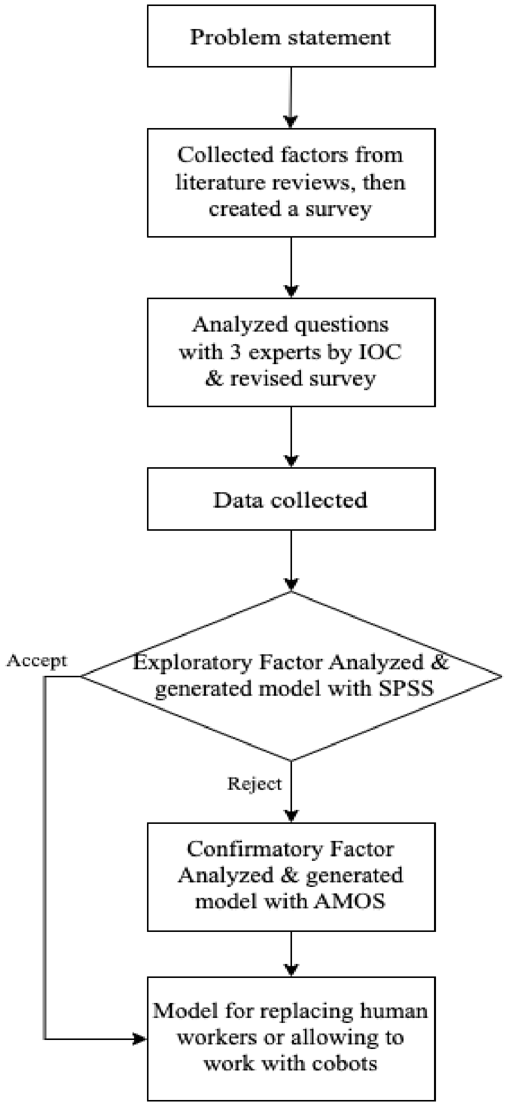

Fig. 9. Methodology of EFA and CFA analyses.

4.1.1. EFA method

The data was categorised, and a new set of factors' components was developed by combining a number of factors discovered through searching related literature. The SPSS programme was used to examine the survey findings that were gathered from experts in the field. The Dimension Reduction tool carried out a factor analysis.

4.1.2. CFA method

To verify the factors' theoretical relationship, the AMOS programme factor-analysed the expert questionnaire findings and categorised them into seven areas based on the literature review, including safety, productivity, quality, system, internal organisation, and external organisation. Since it produced better results than other parameter estimate strategies and utilised smaller sample sizes, the unweighted least squares methodology was used for parameter estimation [25].

4.2. Cobot Implementation through Simulation

Because it was primarily focused on the financial aspect of bringing in cobots, the case study factory did not take other factors like increasing production, decreasing production cycle time, or lowering labour into account. Hence, the case-study cobot implementation model was developed using ARENA simulation to determine the amount of productivity that would increase if cobots were implemented as opposed to traditional labour operations.

5. Result

5.1. Descriptive Statistics of Factors

The average of each of these factors is a representation of the total influence of each aspect on cobot selection decisions. The quality factor was the most overall important factor, with an average value of 4.63, followed by the productivity factors, with an average value of 4.45; the safety factors, with an average value of 3.83; the internal organisation factors, with an average value of 3.78; the system factors, with an average value of 3.65; the ergonomics factor, with an average value of 3.70; and the external organisation factor, with an average value of 3.45 (Table 2).

5.2. Multiple Linear Regression

R-Square was 0.986 (≈1) in Table 3, demonstrating a significant association between the input and output variables. This model was, therefore, helpful in determining whether to use robots to supplement or replace human labour.

Table 2. Mean and standard deviation factors influencing the decision on cobot implementation according to the opinions of the sample group.

No.	Factor	Mean	SD.	Interpretation
Operation				
Safety				
1	Work environments such as working underground or underwater	4.21	0.898	Good
2	Risky work, such as work with too-high or too-low temperatures	4.21	0.842	Good
3	Cobot accidents, such as a faulty cobot sensor, a collision between an operator and a cobot, or uncontrollable jittery movements.	2.40	1.149	Poor
4	Characteristics of workpieces such as sharp workpieces	4.48	0.804	Good
	Total	3.83	0.96	
Ergonomics				
5	Unsuitable or unnatural working posture	3.83	0.908	Good
6	Overexertion, such as lifting heavy objects	4.17	1.057	Good
7	Repetitive task	4.26	0.627	Good
8	Cognitive workload (an amount of mental effort involved in the workload)	2.52	0.804	Poor
	Total	3.70	0.80	
Productivity				
9	Increase production by reducing production cycle time reduce work time	4.55	0.593	Excellent
10	Prevent duplicate work, such as reducing unnecessary steps.	4.36	0.791	Good
	Total	4.45	0.13	
Quality				
11	Produce consistent quality work (According to the standards)	4.62	0.582	Excellent
12	Reduce work errors caused by employees	4.64	0.727	Excellent
	Total	4.63	0.02	
System				
13	Cyber security. The cobot is connected to the network. Information is constantly exchanged. May be exposed to cyber-attacks leading to data leakage.	2.64	0.821	Poor
14	Data management on enterprise systems concerns the management of data on enterprise systems, e.g., due to insufficient system capacity for data calculations. This caused a delay in the response of cobots.	3.14	1.002	Fair
15	Cobot maintenance	3.57	0.966	Good
16	How easy/difficult to install cobots	3.57	1.039	Good

No.	Factor	Mean	SD.	Interpretation
17	Lifespan of the cobot.	3.69	0.643	Good
18	Flexibility to modify if new functionality	3.95	0.825	Good
19	Mobility of cobots with wheels or on AGV and Fully autonomous mobile cobot.	4.10	0.726	Good
20	Software	3.90	0.759	Good
21	Hardware	3.48	0.671	Fair
22	Self-aware intelligence	3.79	1.048	Good
23	Cobot features such as payload, cobot reach	3.79	0.813	Good
24	How easy/difficult to use a controller or interface in a cobot (human-machine interface)	4.17	0.537	Good
	Total	3.65	0.42	
Non-operation				
Internal organisation				
25	Support from senior management	4.14	0.647	Good
26	Prevent human immorality	2.81	1.234	Poor
27	Reduce the cost of hiring staff	3.90	1.008	Good
28	Project return analysis	4.00	0.963	Good
29	Increase the credibility of the organisation	3.24	1.165	Fair
30	Availability of IT infrastructure	4.05	0.795	Good
31	Availability of IT specialists	4.07	0.838	Good
32	Time availability	3.79	0.813	Good
33	Training and motivation	3.57	0.914	Good
34	Limitation of the factory site.	4.24	0.850	Good
	Total	3.78	0.45	
External organisation				
35	Tax benefits	2.90	0.878	Poor
36	Changing industry structure through advanced knowledge and technology (Industry 4.0).	3.93	0.745	Good
37	Prevent the problem of labour shortage.	3.64	0.692	Good
38	Compete with other companies in the industry.	3.86	0.647	Good
39	Meet the needs of customers.	3.50	0.741	Good
40	Government support for cobots in factories.	3.40	0.939	Fair
41	Building alliances with robot manufacturers and system integrators receiving support in the future	2.93	0.947	Poor
	Total	3.45	0.12	

Table 3. Output of multiple regression model.

R	R Square	Adjusted R Square	Std.Error of the Estimate
.993	**.987**	.974	.02669

Table 4. Stepwise multiple regression analysis result.

Factor	Unstandardised Coefficients		Standardised Coefficients	t	Sig
	B	Std. Error	Beta		
(Constant)	0.148	0.160		0.925	0.377
System	0.304	0.013	0.550	23.251	0.000
Internal organisation	0.212	0.012	0.412	18.196	0.000
Ergonomic	0.096	0.010	0.232	9.766	0.000
External organisation	0.181	0.011	0.343	16.414	0.000
Safety	0.079	0.008	0.233	9.819	0.000
Quality	0.055	0.008	0.156	6.845	0.000

Table 4 shows that all factors were statistically significant at a p-value of 0.05, and the independent variables with the greatest impact on the dependent variable were discovered using the standardised coefficients. The variables that had the biggest effects on the dependent variable were the system, internal organisation, ergonomics, external organisation, safety, and quality, in that order. The expected equation could have the following form:

$$Y = 0.315 + 0.304X_1 + 0.212X_2 + 0.096X_3 + 0.181X_4 + 0.079X_5 + 0.055X_6 \quad (1)$$

where

Y = The decision to implement cobot
X_1 = System
X_2 = Internal organisation
X_3 = Ergonomics
X_4 = External organisation
X_5 = Safety
X_6 = Quality

5.3. Exploratory Factor Analysis

Table 3 demonstrates how the quantitative survey findings were assessed using the EFA method and the SPSS programme. The 41 components were too numerous, so it was necessary to hypothetically combine them to provide a framework for selecting which cobots to use. The 41 elements were divided into 13 components, and for each component, the factors were conceptually unconnected. Furthermore, CFA was used to confirm that the defined factor groupings were theoretically related.

5.4. Confirmatory Factor Analysis

Based on the pertinent concepts, 41 factors were divided into seven categories to build a model. As shown in Fig. 10, the CFA method was used to assess the quantitative survey findings using the Amos programme. The model takes into account how well it fits the given empirical data. Factor loading for every factor ranged from -0.843 to 1.235. Also, 462.783 was the chi-square value. The RMR value came in at 0.114. The GFI value was measured at 0.673. In terms of AGFI, it was 0.628. According to the results, it is decided that this model does not satisfy the standards required to be accepted and that it has to be altered and reevaluated.

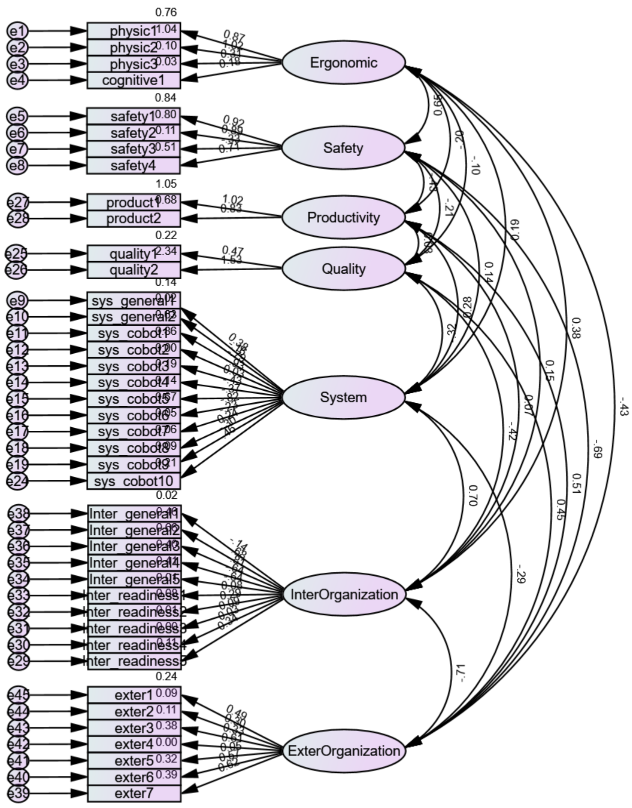

Fig. 10. Correspondence model for all factor data.

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Table 5. Components from exploratory factor analysis.

Factor	Component												
	1	2	3	4	5	6	7	8	9	10	11	12	13
8	**0.833**												
1	**0.828**												
23	**0.702**		0.398										
29	**0.594**	-0.352	0.321										
13	**0.592**						0.406						
15	**0.559**												0.532
19		**0.822**				-0.419							
16		**0.802**											
2		**0.784**		-0.331									
34		**0.748**											
14		**0.556**						-0.387		0.377		-0.378	
27			**0.823**										
22			**0.732**	-0.311						0.331			
36			-0.580		0.356				-0.315				
20			0.511				0.490		0.361				
21			0.418		-0.319			-0.368		0.366		-0.314	
18				**0.889**									
3				**0.604**						0.312			
39				**0.568**	0.458				0.342		-0.352		
41			-0.463	**0.567**									
26			0.364	-0.425								-0.393	
37					**0.877**								
5					**0.756**			-0.335					
24					**0.655**	-0.411			0.393				
40						**0.759**							
32						**0.751**							
35	0.347					-0.674			0.357				
31							**0.753**					-0.300	
25	0.443						**0.707**						
30							**0.542**				0.490		
33								**0.854**					
9								**0.847**					
4									-0.842				
38						0.324			**0.728**				
10										**0.826**			
11	0.455									**0.639**			
7											**0.861**		
12				-0.356	0.364						-0.429		
17												**0.873**	
28	0.438			-0.376							0.336	**0.507**	
6													**0.851**

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The model has been altered to enhance the harmony shown in Fig. 11 by taking into account the model's suitability with actual data. The factor loadings for each factor range from 0.042 to 0.991. 0.35 was the relative chi-square value. RMR came in at 0.092. GFI is calculated at 0.784. AGFI score of 0.734%. Hence, this model met the required standards by demonstrating the statistical comparison with the predetermined criteria, as presented in Table 6.

Table 6. Compare the result with the specified criteria.

	Criterion	Result	Interpretation
Relative chi-square (Chi-square/df)	≈ 0	= 141.333/406 =0.35	Good
RMR (Root Mean Residual)	≈ 0	0.092	Marginal
GFI (Goodness of Fit Index)	≈ 1	0.784	Marginal
AGFI (Adjusted Goodness of Fit Index)	≈ 1	0.734	Marginal

The relationship between the groups is displayed in Table 7. The ergonomics factor group had a value of 0.656, making the safety factor group the correlated group. The association between the productivity factor group and the external factor group was 0.527. At 0.12, there was a link between the internal factor group and the ergonomic factor group. The association between the external factor group and the quality factor group was 0.066. The majority of the connections between the groupings were unrelated.

The model's agreement with the actual data displayed in Fig. 11 led researchers to conclude that each factor had a factor loading that ranged from 0.042 to 0.991. The work settings, which include the safety factor group, had the greatest weight value of 0.912, followed by the risky job, which had a weight value of 0.798, and the features of workpieces, which had a weight value of 0.912 as the final factor. The factors related to ergonomics, work conditions, and overexertion had the greatest weight values (0.891), followed by the factors related to inappropriate posture (0.708) and repetitive tasks (0.284). Regarding the quality aspect, producing consistently high-quality work came in second with a weight value of 0.715, trailing only the reduced work errors brought on by employees, which had a weight value of 0.991. The factor for reducing duplication of effort weighted 0.689, while the factor for enhancing production weighted 0.814 in the productivity factor groups.

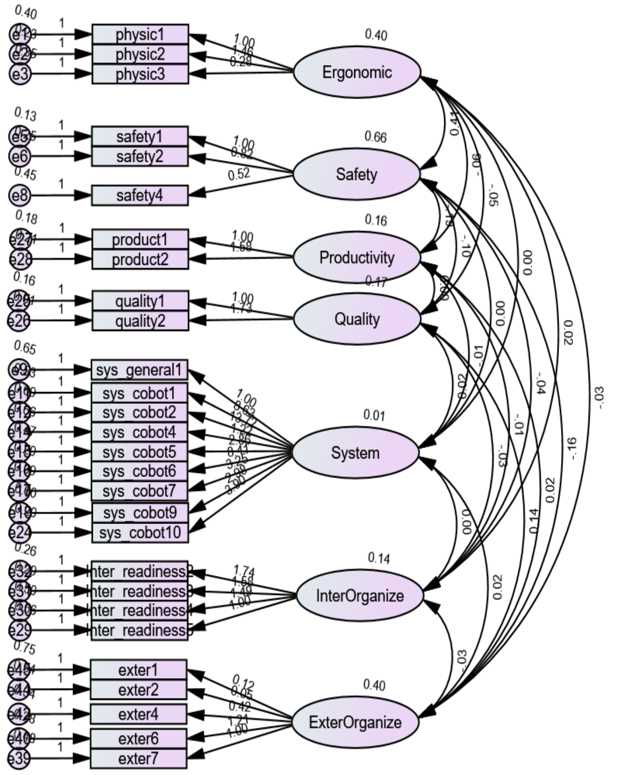

Fig. 11. Adjusted correspondence model.

The controller or interface difficulty in the cobot was 0.526, the software program was 0.803, the cobot maintenance was 0.647, and the cobot installation was 0.957 in the system factor group. The cobot's hardware was 0.351, its mobility was 0.286, its features were 0.108, and its network connection's cybersecurity was 0.088. With a value of 0.789, the availability of IT professionals was the internal factor with the highest weight, followed by time availability (0.737), training and motivation (0.618), and industrial site constraints (0.447).

In the group of external factors, the element with the highest weight is cobot adoption in factories received 0.823 points of government backing while forming partnerships with robot manufacturers received 0.676 points. It was 0.417 to compete with other companies in this industry. Finally, the factor for tax benefits was 0.09, followed by the industry structure change factor of 0.042. Table 7 displays a summary of the weighting factors for each component.

The majority of the relationships in each group were not related to one another, according to Table 8, which displays the relationship between groups of components. The safety factor group, which has a value of 0.791, is similar group to the ergonomic factor group. The relationship between the system factor group and the quality factor group was 0.646. The correlation between the quality factor group and the external organisation factor group was 0.528. At 0.403, the system factor group and the external organisation factor group were correlated. At 0.096, there was a relationship between the internal organisation factor group and the ergonomic factor group.

At 0.095, the external organisation factor group and the productivity factor group were connected. The relationship between the system factor group and the internal organisation factor group was 0.01. The relationship between the safety factor group and the system factor group was 0.01.

The work environment has the largest weight among safety elements from the group of primary factors, it was shown. Overexertion is the ergonomics category's biggest factor. The most important productivity aspect is avoiding task duplication. The quality parameters that decrease employee-caused job mistakes are given the most weight. The cobot installation process's complexity/easiness is the system factor that is given the most weight. The availability of IT skills is the most significant internal organisational factor. Moreover, government assistance is the most significant external organisational force.

Table 7. Standardised Regression Weights each group.

Standardised Regression Weights			**Estimate**
safety1	<---	Safety	0.912
safety2	<---	Safety	0.798
safety4	<---	Safety	0.529
physic2	<---	Ergonomic	0.891
physic1	<---	Ergonomic	0.708
physic3	<---	Ergonomic	0.284
quality2	<---	Quality	0.991
quality1	<---	Quality	0.715
product2	<---	Productivity	0.814
product1	<---	Productivity	0.689
sys_cobot2	<---	System	0.957
sys_cobot6	<---	System	0.803
sys_cobot1	<---	System	0.647
sys_cobot10	<---	System	0.526
sys_cobot7	<---	System	0.351
sys_cobot5	<---	System	0.286
sys_cobot9	<---	System	0.266
sys_cobot4	<---	System	0.108
sys_general1	<---	System	0.088
Inter_readiness2	<---	InterOrganize	0.789
Inter_readiness3	<---	InterOrganize	0.737
Inter_readiness4	<---	InterOrganize	0.618
Inter_readiness5	<---	InterOrganize	0.447
exter6	<---	ExterOrganize	0.823
exter7	<---	ExterOrganize	0.676
exter4	<---	ExterOrganize	0.417
exter2	<---	ExterOrganize	0.042
exter1	<---	ExterOrganize	0.09

Table 8. Correlations between groups.

Correlations			**Estimate**
Safety	**<-->**	**Ergonomic**	**0.791**
Safety	**<-->**	**System**	**0.01**
Safety	<-->	Quality	-0.296
Safety	<-->	Productivity	-0.589
Ergonomic	<-->	System	-0.088
Ergonomic	<-->	Quality	-0.173
Ergonomic	<-->	Productivity	-0.222
System	**<-->**	**Quality**	**0.646**
System	<-->	Productivity	-0.309
Quality	**<-->**	**Productivity**	**0.009**
InterOrganize	<-->	ExterOrganize	-0.136
System	**<-->**	**ExterOrganize**	**0.403**
Quality	**<-->**	**ExterOrganize**	**0.528**
Safety	<-->	ExterOrganize	-0.316
Ergonomic	<-->	ExterOrganize	-0.086
Productivity	**<-->**	**ExterOrganize**	**0.095**
Ergonomic	**<-->**	**InterOrganize**	**0.096**
Safety	<-->	InterOrganize	-0.133
Productivity	<-->	InterOrganize	-0.067
Quality	<-->	InterOrganize	-0.193
System	**<-->**	**InterOrganize**	**0.01**

5.5. Cobot Implemented Simulation

The simulation model is created to demonstrate the validity of the notion that employing cobots can boost output, cut down on labour requirements, decrease the need for personnel, and save energy. According to the case study, a firm intended to use cobots for sorting operations since they were only concerned with the financial aspect and neglected other considerations. As seen in Fig. 12, the current procedure entails sorting the workpiece and printing the label on the envelope. As shown in Fig. 13, the sorting, printing, and labelling procedures were merged into a single process for this study so that cobots and humans could collaborate.

The process is depicted in Fig. 13 as being integrated, with cobots doing the sorting and label printing jobs and humans placing the printed labels on the envelope. The task that is submitted for the procedure is to begin. The cobot will pick up the item and arrange it according to the type of packing. If auto packaging is present, the stamping process will start. If manual packaging is necessary, the cobot will scan the bar code on the cart note, sending a print command to the printer to print the workpiece label, which the staff will then stick to the envelope. The properties of the cart note that was inserted into the work tray are shown in Fig. 15. Figure 16 depicts the cobots' and workers' workstations.

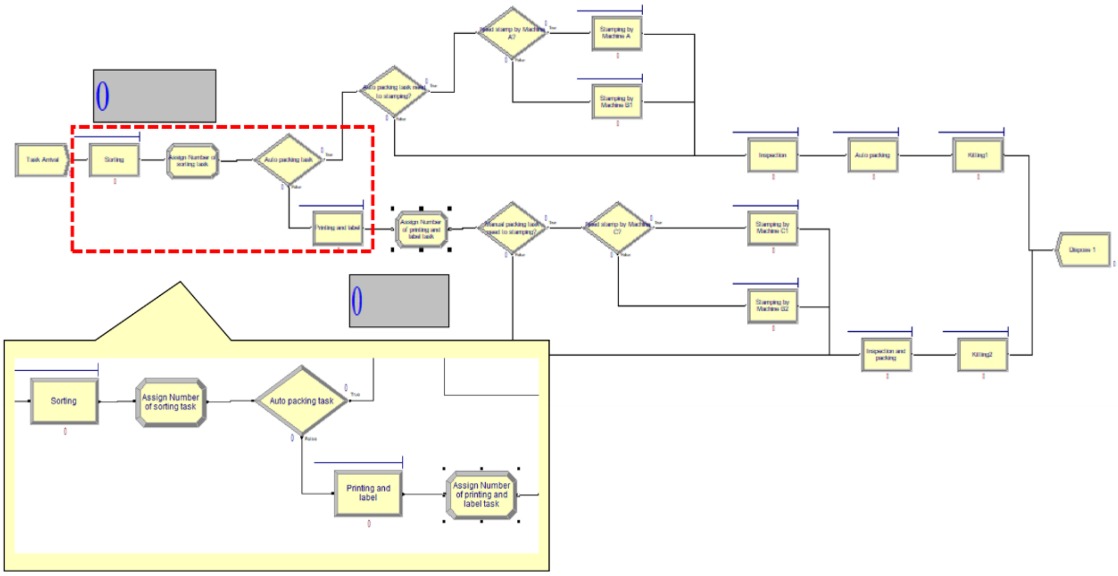

Fig. 12. Simulation model of the current operations.

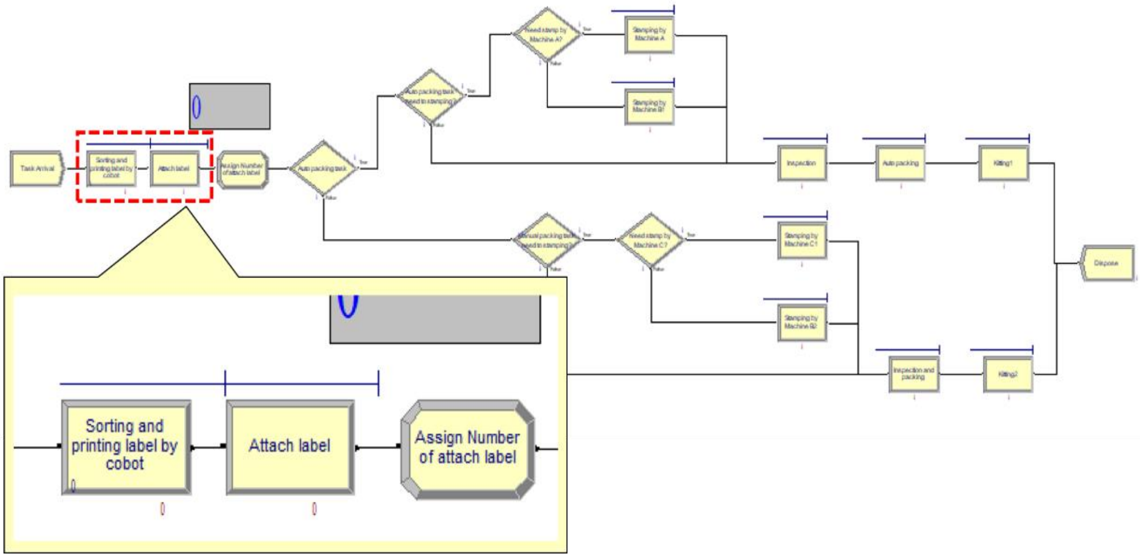

Fig. 13. Simulation model of the cobot implementation.

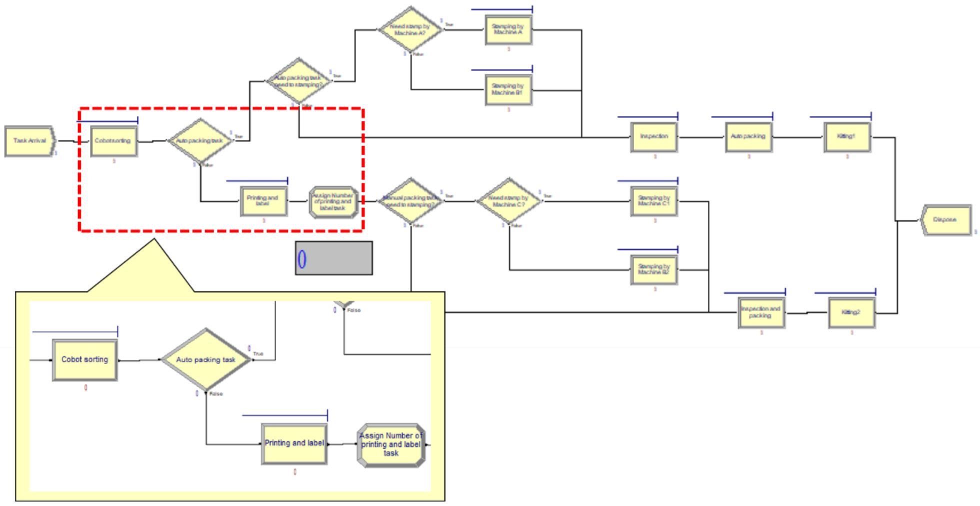

Fig. 14. Simulation model of cobot replacement.

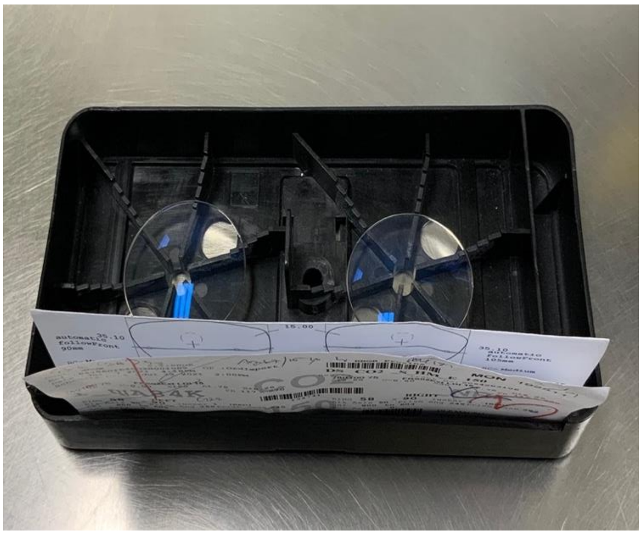

Fig. 15. The appearance of the workpiece that the workpiece is inserted into the tray.

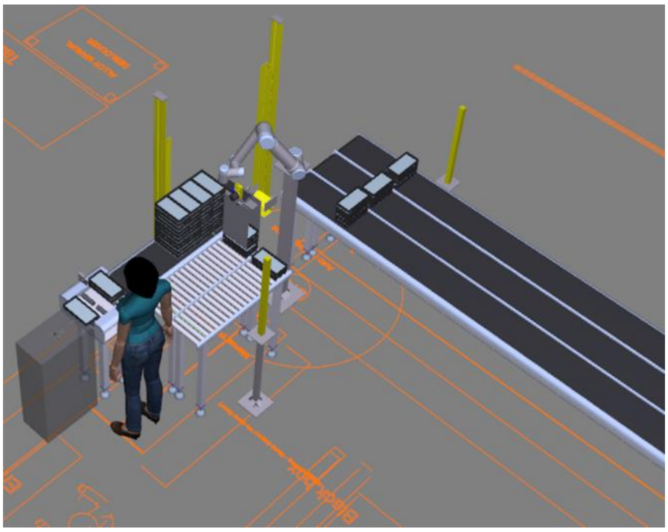

Fig. 16. Cobot and worker workstation simulation.

Table 9 compares the productivity of the model of existing operations and the model from before the deployment of cobots. When cobots were introduced, the sorting and label printing operations were integrated into one, enabling a quicker process than the previous one. There was now only one worker needed instead of the previous one of three workers, which reduced 66.67%. The increase in produced workpieces was 181 pieces or 2.55%. WIP shrank by 103 pieces or 6.78%. The modified process's waiting time was 5.0979 seconds, compared to the prior process's waiting time of 62.6878 seconds. The wait time was reduced by 91.87% or 57.5899 seconds. Moreover, 5.6491 pieces remained in the former process queues, whereas 0.6792 pieces remained in the new process queue, which is an 87.98% reduction.

For the sorting operation to be replaced by cobots, for the same printing and labelling tasks, the existing three workers were decreased to two, a decrease of 33.33%. This results in 42 more items, or 0.59% more workpieces, being shipped. WIP fell by 16 items or 1.05%. The delay was cut by 3.142 seconds or 5.01%. The total number of workpieces waiting throughout the initial process was 5.6491, and that number decreased by 0.3071 or 5.436%.

The research investigation found that it was consistent with the theory that using cobots in the workplace can increase work productivity and help decrease the number of employees, steps needed to get ready for work, and energy used for work, according to the results of the study of modelling when using cobots in factories. In addition, it improved the working wellness of the workforce. Compared to cobot replacement methods, cobot adoption in cooperative operations produced higher productivity. However, utilising cobots to replace workers offers benefits in terms of the factory's space utilisation and labour costs, and if cobots were employed in other factory operations, production could similarly increase.

5.6. Implementation of the Decision-Making Guideline for Adopting Cobots

Considering a case study on the implementation of cobots in manufacturing, the case study was traditionally only taken into account in terms of financial considerations, such as labour costs and payback periods, in comparison to the savings from labour reduction. It is necessary to think about the initial component, which is the internal aspects that should be taken into account, to find a decision-making guideline for the adoption of cobots in a new factory. The first consideration when assessing an organisation's readiness was the time available for investigating the usage of cobots in job search activities. To decide whether the IT infrastructure is ready if cobots are put into operations, take into account the preparedness of the IT specialists and infrastructure. To encourage staff members to be prepared and eager to work with cobots, incentive training should also be taken into account while deploying cobots. Take into account the factory's space restrictions and decide if there is enough room or if you want to reduce the working area.

Table 9. Productivity summary between the current operating model and the cobot implement the model.

Current operations	Cobot implementation	Cobot replacement	Productivity	
			Cobot implementation	Cobot replacement
2 Process • Sorting • Printing and label	Combine the sorting process and the printing and label process into one.	2 Process • Cobot sorting • Printing and label		
Number of employees • Sorting: one person • Printing and labelling: two person	Number of employees • Attach label: one person	Number of employees • Printing and labelling: two persons	The number of employees decreased by 66.67%	The number of employees decreased by 33.33%
Energy expenditure per person (Refer to the weight of the staff at 60 kg.) • Sorting 1344.68 kcal/8 hr • Printing and label 963.72 kcal/8 hr	Energy expenditure per person • Attach label 1243.97 kcal/8 hr	Energy expenditure per person • Printing and label 997.61 kcal/8 hr		
Number out • 7109	Number out • 7290	Number out • 7151	Production of the task increased by 2.55%.	Production of the task increased by 0.59%.
WIP • 1518	WIP • 1415	WIP • 1502	WIP decreased by 6.785%	WIP decreased by 1.05%
Waiting time • Sorting 2.3126 seconds • Printing and label 60.3752 seconds **Total** 62.6878 seconds	Waiting time • Sorting and printing 5.0979 seconds • Attach label 0 seconds **Total** 5.0979 seconds	Waiting time • Sorting 2.326 seconds • Printing and label 57.22 seconds **Total** 59.546 seconds	Waiting time decreased by 91.87%	Waiting time decreased by 5.01%
Number of workpieces waiting • Sorting 0.3084 pieces • Printing and labelling 5.3407 pieces **Total** 5.6491 pieces	Number of workpieces waiting • Sorting and printing 0.6792 pieces • Attach label 0 pieces **Total** 0.6792 pieces	Number of workpieces waiting • Sorting 0.3096 pieces • Printing and labelling 5.033 pieces **Total** 5.342 pieces	Number of workpieces waiting decreased by 87.98%	Number of workpieces waiting decreased by 5.436%

Regarding the external elements that need to be taken into account, offering and customising cobots to fulfil consumer demands and satisfaction can help meet customer needs by meeting customer needs. Regarding the issue of a labour shortage, Thailand is now dealing with the issue of an ageing population, which will lead to labour shortage issues in the future. Cobots can be employed for this work to assist in alleviating labour shortages. The ergonomic component should be considered for the worker because the work leads to

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fatigue. The amount of fatigue experienced at work can be decreased with the use of cobots by taking into account poor working postures. The sorting activity at the case study factory has the potential to cause an incorrect or uncomfortable posture as people reach for the workpiece. Because the workpiece is on a tray, most employees stack the trays on tall levels, which adds to their workload. Figure 17 illustrates how the workpiece must raise a substantial amount of weight to be moved. As shown in Fig. 17, when moving the workpiece, it must lift a large amount of weight.

The case study delivers jobs that are divided by labour elements for repeated tasks. The repetitive movements in the work define it, causing extreme exhaustion as a result of repeatedly exercising the same muscles. If so, whether or not the working posture appears incorrect, the risk must be evaluated. Analyses of the ergonomic risks are also taken into consideration. The factory case study's work is an example of a form of work that requires movement. The REBA and NIOSH methodologies for ergonomic risk assessment would be suitable because they take into account repetitive motion, the weight of the load, and working posture.

With regard to the productivity factor, cobots can improve productivity and be able to shorten production cycle times and labour hours. When cobot adoption was modelled, productivity increased by 2.55% compared to the prior condition without cobot adoption, and the number of components waiting in process (WIP) decreased by 6.785%. The waiting time was cut in half, and there were 87.98% fewer waiting entities. To simplify the complex working procedures, cobots and human workers in the manufacturing case study can integrate the label printing and splitting processes into a single operation. Regarding the quality aspect, the usage of cobots in the workplace can reduce human error because fatigue can be a factor in human error.

Errors can be minimised in this area by using cobots in the workplace. Regarding the safety aspect, it can be noted that the workpiece that the worker was holding in the case study factory had a relatively sharp edge. As a result, consideration must be given to the workpiece or working object. The system factor should also be taken into account when cobots are continually connected to the network and exchanging information, which makes them vulnerable to cyberattacks that could reveal the factory's trade secrets. The manufacturer has to consider concerning the cobots' maintenance and how frequently they need to be done. When putting cobots to use, installation complexity or simplicity have to be taken into account. In addition, whether cobots are stationary, AGV-based, or mobile (wheeled cobots), cobot agility must be taken into account while adjusting cobot activities. Consideration should be given to a computer programme that directs the cobot's direction, speed, and force. Also, taking into account the cobots' hardware and other structural elements, the amount of weight the cobot can support and its reach are regarded as the cobot's properties. The case study's cobots are simple to use and comprehend, especially in light of how simple it is to use the cobots' controller or user interface.

Fig. 17. Gestures when lifting workpiece tray stacks.

6. Conclusion

The objective of this research is to develop a framework for making decisions regarding whether to use robots to complement human labour or to completely replace it. This study's starting point is a challenge faced by the case study factory that wishes to introduce cobots to the workplace. However, only financial aspects—such as labour costs and payback times in comparison to labour savings, were taken into account. There is no decision-making framework for the introduction of cobots, which would allow for the use of operational robots in collaboration with humans or the use of robots to replace labour. In this study, theories and literature on system factors, internal organisation factors, productivity factors, quality factors, and external organisation variables were reviewed. After gathering the factors, developing the questionnaire, and using the results for exploratory factor analysis (EFA) and confirmatory factor analysis (CFA), the process was completed. The case study manufacturing operation might use the confirmatory model effectively. The use of replacement cobots, which can boost productivity and assist in reducing work steps, staff count, energy use at work, and employee ergonomics, was superior to the use of cobots in collaborative operations. It can contribute to a 2.55% rise in productivity, WIP fell by 6.78 per cent, the waiting time was cut in half, and there were 87.98% fewer workpieces waiting. Regarding industrial space restrictions and employee expenses, using cobots to replace employees provides benefits. The outcomes of the expert's judgement may differ according to the field or type of work undertaken, and the results may or may not be applicable to other applications. Future studies may therefore examine different sectors to get the wider perspective they need.

References

[1] C. Abhinorasaeth, K. Kalyanamitra, S. Niyomyaht, and T. Lakkanapichonchat, "Robot cluster development policy implementation," *Journal of Educational Review Faculty of Education in MCU*, vol. 8, no. 3, pp. 58-72, 2021.

[2] M. C. Gombolay, C. Huang, and J. Shah, "Coordination of human-robot teaming with human task preferences," in *2015 AAAI Fall Symposium Series*, September, 2015.

[3] Y. Cohen, S. Shoval, and M. Faccio, "Strategic view on cobot deployment in assembly 4.0 systems," *IFAC-PapersOnLine*, vol. 52, no. 13, pp. 1519-1524, 2019.

[4] A. Kinast, K. F. Doerner, and S. Rinderle-Ma, "Combining metaheuristics and process mining: Improving cobot placement in a combined cobot assignment and job shop scheduling problem," *Procedia Computer Science*, vol. 200, pp. 1836-1845, 2022.

[5] B. Gajšek, S. Šinko, T. Kramberger, M. Butlewski, E. Özceylan, and G. Đukić, "Towards productive and ergonomic order picking: Multi-objective modeling approach," *Applied Sciences*, vol. 11, no. 9, p. 4179, 2021.

[6] K. Sudthida, *Ergonomics and Organization of Work*. Dec. 1997.

[7] Thailand Institute of Occupational Safety and Health (Public Organization), *Ergonomics Manual for Lifting and Handling Operations Improvement*. 2018.

[8] L. McAtamney and E. N. Corlett, "RULA: A survey method for the investigation of work-related upper limb disorders," *Applied Ergonomics*, vol. 24, no. 2, pp. 91-99, 1993.

[9] S. Hignett and L. McAtamney, "Rapid entire body assessment (REBA)," *Applied Ergonomics*, vol. 31, no. 2, pp. 201-205, 2000.

[10] E. Occhipinti, "OCRA: A concise index for the assessment of exposure to repetitive movements of the upper limbs," *Ergonomics*, vol. 41, no. 9, pp. 1290-1311, 1998.

[11] T. R. Waters, V. Putz-Anderson, and A. Garg, *Applications Manual for the Revised NIOSH Lifting Equation*. 1994.

[12] A. C. Simões, A. Pinto, J. Santos, S. Pinheiro, and D. Romero, "Designing human-robot collaboration (HRC) workspaces in industrial settings: A systematic literature review," *Journal of Manufacturing Systems*, vol. 62, pp. 28-43, 2022.

[13] X. Brioso, D. Murguia, and A. Urbina, "Teaching takt-time, flowline, and point-to-point precedence relations: A Peruvian case study," *Procedia Engineering*, vol. 196, pp. 666-673, 2017.

[14] P. Hongsai, "Loss reduction in knockdown furniture factory," master's thesis, Department of Industrial Engineering, Faculty of Engineering, Chulalongkorn University, 2019.

[15] C. Piputsitee, "Economics of project analysis. economics," Kasetsart University, 2011.

[16] A. A. Malik and A. Bilberg, "Collaborative robots in assembly: A practical approach for tasks distribution," *Procedia Cirp*, vol. 81, pp. 665-670, 2019.

[17] N. Gjeldum, A. Aljinovic, M. Crnjac Zizic, and M. Mladineo, "Collaborative robot task allocation on an assembly line using the decision support system," *International Journal of Computer Integrated Manufacturing*, vol. 35, no. (4-5), pp. 510-526, 2022.

[18] F. Ranz, T. Komenda, G. Reisinger, P. Hold, V. Hummel, and W. Sihn, "A morphology of human robot collaboration systems for industrial assembly," *Procedia CiRp*, vol. 72, pp. 99-104, 2018.

[19] A. C. Simões, A. L. Soares, and A. C. Barros, "Factors influencing the intention of managers to adopt collaborative robots (cobots) in manufacturing organisations," *Journal of Engineering and Technology Management*, vol. 57, p. 101574, 2020.

[20] A. Papetti, M. Ciccarelli, C. Scoccia, and M. Germani, "A multi-criteria method to design the collaboration between humans and robots," *Procedia CIRP*, vol. 104, pp. 939-944, 2021.

[21] N. Berx, W. Decré, I. Morag, P. Chemweno, and L. Pintelon, "Identification and classification of risk factors for human-robot collaboration from a system-wide perspective," *Computers & Industrial Engineering*, vol. 163, p. 107827, 2022.

[22] N. Sánchez and M. Cahill, "The strengths and weaknesses of factor analysis in predicting Cuban GDP," *Cuba in Transition*, vol. 8, pp. 273-88, 1998.

[23] K. Vanichbuncha, *Structural Equation Modeling (SEM) with AMOS* (in Thai). Chulalongkorn University, 2013.

[24] A. Koonkaew, *Choosing Basic and Advanced Statistics for Research. Data Analysis and Results Presentation* (in Thai). Chulalongkorn University, 2023.

[25] H. Koğar and E. Y. Koğar, "Comparison of different estimation methods for categorical and ordinal data in confirmatory factor analysis," *Journal of Measurement and Evaluation in Education and Psychology*, vol. 6, no. 2, 2015.

[26] P. Chutima, "Research trends and outlooks in assembly line balancing problems," *Engineering Journal*, vol. 24, no. 5, pp. 93-134, 2020.

[27] P. Chutima, "A comprehensive review of robotic assembly line balancing problem," *Journal of Intelligent Manufacturing*, vol. 33, no. 1, pp. 1-34, 2022.

[28] P. Chutima, "Assembly line balancing with cobots: An extensive review and critiques," *International Journal of Industrial Engineering Computations*, vol. 14, no. 4, pp. 785-804, 2023.

[29] P. Chutima and A. Khotsaenlee, "Multi-objective parallel adjacent U-shaped assembly line balancing collaborated by robots and normal and disabled workers," *Computers & Operations Research*, vol. 143, p. 105775, 2022.

[30] A. Khotsaenlee and P. Chutima, "Many-objective parallel adjacent u-shaped assembly line balancing

operated by human and robot," in *2021 3rd International Conference on Management Science and Industrial Engineering*, 2021, pp. 214-220.

[31] S. Ngampanich and P. Chutima, "Many-objective mixed-model parallel assembly line balancing utilizing normal workers, disabled workers, and robots," in *Proceedings of the 4th International Conference on Management Science and Industrial Engineering*, 2022, pp. 311-317.

[32] C. Prakong and P. Chutima, "Many-objective assembly-line parts feeding decisions in automotive industry," in *Proceedings of the 4th International Conference on Management Science and Industrial Engineering*, 2022, pp. 302-310.

[33] C. Pacharatham and P. Chutima, "Facility location placement optimisation for bagged cement distribution during the COVID-19 pandemic," *Engineering Journal*, vol. 27, no. 7, pp. 75-95, 2023.

Chanatip Thongdonnoi, photograph and biography not available at the time of publication.

Parames Chutima, photograph and biography not available at the time of publication.

Arisara Jiamsanguanwong, photograph and biography not available at the time of publication.

Oran Kittithreerapronchai, photograph and biography not available at the time of publication.

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