E-ISSN: 2717-2937 | P-ISSN: 2783-1337

International Journal of Research in Industrial Engineering

www.riejournal.com

Int. J. Res. Ind. Eng. Vol. 10, No. 4 (2021) 286–294.

Paper Type: Research Paper

Analyzing the Impact of 5S Implementation in the Manufacturing Department: A Case Study

Tasnim Ahmed Tahasin[1], Himadri Sen Gupta[2,*], Noshin Tasnim Tuli[1]

[1] Department of Industrial and Production Engineering, Military Institute of Science and Technology, Dhaka, Bangladesh; tasnimtat@gmail.com; noshintasnim06@gmail.com.

[2] School of Industrial and Systems Engineering, University of Oklahoma, Norman, Oklahoma 73019, USA; hgupta.ipe.kuet@gmail.com.

Citation:

Tahasin, T. A., Gupta, H. S., & Tuli, N. T. (2021). Analyzing the impact of 5S implementation in the manufacturing department: a case study. *International journal of research in industrial engineering, 10*(4), 286-294.

Received: 25/06/2021 Reviewed: 15/07/2021 Revised: 26/08/2021 Accept: 18/09/2021

Abstract

5S is a systematic approach that helps to organize a workplace for increasing efficiency and reduce wasting of productivity by providing an organized safe environment. The objective of this paper is to emphasize the implementation of 5S principles for the workplace by reflecting a tooling problem of a manufacturing unit. This article examines the challenges experienced in the implementation of 5S methodology to optimize labor and safety in a manufacturing department by showing the gap of productivity caused while not having 5S methodology in workplaces. The time consumption analysis of 5S implementation through shadow boarding demonstrates workers who have been able to perform work more efficiently along with a significant reduction of searching time of tools. The results showed that 5S along with the shadow boarding technique creates improvement in efficiency, workspace, equipment search time, working environment and safety. Consequently, this shadow boarding technique would strongly support the objectives of multinational companies to achieve continuous improvement and higher performance.

Keywords: 5S Lean tool, Lean manufacturing, Shadow boarding foam, Visual inspection, 7 Waste.

1 | Introduction

5S is the introductory method of lean manufacturing which energizes the way industries conduct production. Mainly it consists of 5 steps which are Sort, Set in Order, Shine, Standardize, Sustain. (See *Fig. 1*) High levels of management and the organizational Systems as well as the Management provision tools have been the two main modules of 5S. 5S is also the segment of kaizen which expedient "Transformation for Finer". It supports the ideology of Total Quality Management (TQM) as well as the first Lean method which expedites the use of lean techniques in order to enhance the structure's action. 5S has been one of the successional activities which fabricates in such a way that raises the standard of work environment, sense of responsibility and team commitment which further result in cozy and methodical workspaces. The better equipment reliability along with the reduced work time will boost up the production, the classification, the maintenance of workspace and this will further result in the depletion of cost. Moreover, 5S has always been enhanced the employee's self-esteem and employee's commitment.

Corresponding Author: hgupta.ipe.kuet@gmail.com

http://dx.doi.org/10.22105/riej.2021.229039.1230

All the multinational companies around the globe give prime importance to the quality and productivity of the product they produce, which solely depends up-on accidents, down time in the production, working environment, housekeeping technique etc. On the other hand, in the manufacturing environment, Lean Manufacturing has been considered a dynamic learning method which reduces the wastage and continuously tries to increase utilization of the resources and activities that add value from the customer's perspectives.5S has always been one of the initiatives which is responsible for the revolution in different types of industries. Different industries such as manufacturing and business sectors have been assigned with devastating stages before the implementation of 5S. Earlier, they have been involved with disorganized tool setting, filthy and unbearable environment with ineffectual process flow. Therefore, a vulnerable situation was created which enhanced the cost of production process due to wastage leading to the increasing of lead time to find the suitable equipment which are required. Complications has been encountered when the company is working on the project having scheduled due date. The purpose of this study has been the implementation of 5S which is the best solution of the given issues. Its further results in healthy environment, minimization of waste and enhancing profit, diminishing non-value adding time, improvement in productivity and quality as well as improvising the efficiency of the process by Shadow boarding. Shadow Boards are equipment that has been used in purpose of systemizing in the work plant which results deterioration of cost by storing the suitable tools in needed locations nearer to workstations so thus reducing waste and enhancing the efficiency of the process. Shadow Board applied basically in the stages of the execution of 5S.

2 | Literature Review

Jiménez et al. [1] showed 5S methodology application in university organiza-tions to create an organizational culture and applied both in the processes related to the students learning, and in the teaching and non-teaching activitie. Phogat [2] presented a theory of organizational culture and management in his paper and also discussed about Lean perspective and possibilities of tracking changes from the implementation of Lean. It turns the problem areas of the company to an improvement of efficiency and value adding through the implementation of Lean in the warehouse of the shipyard.

An industry application of 5S lean technology at a Prefab factory has been pre-sented by Al-Aomar [3]. The process flow at the Prefab facility is not stream-lined due to the wide variety in product specifications, the growing demand, the push production policy. Therefore, 5S lean technology is utilized for developing an infrastructure of continuous process improvement rations. The study by Singh and Ahuja [4] revealed that 5S implementation has improved the employees motivation, which has been demonstrated by significant increase in Kaizen suggested and implemented at workplace, thereby enhancing the value added per employee in the organization. After that the study of Yang et al. [5] explores the relationships between lean manufacturing practices, environmental management and business performance outcomes. It resolves the conflicts between lean manufacturing and environmental performance. On the other hand, the review of the use of 5S in healthcare services is discussed by Yang et al. [5]. The documentation about 5S, Lean, ways to implement 5S in healthcare settings, combinations of 5S and other tools and suggestions have been evaluated. Melton's [6] re-search emphasis on the complete change of the businesses by the implementation of lean which lead to improve the Performance improvements across the whole supply chain thus increase in business performance. The study of Omogbai and Salonitis [7] showed the short run dynamic implications of the sorting aspect of 5S which is investigated using system dynamics. It also showcases some intriguing relationships between 5S and other lean practices as well as system performance.

Then, the paper of Veres et al. [8] exhibited the relationship between 5S evolution and productivity in a local company from Mureș Country, Romania, which operates in automotive industry for over 10 years. Here, 5S method is very significant which have a positive correlation to overall performance of production results. Furthermore, the research paper displayed the methodology action steps, resources required and the target outcomes for the implementation of 7S by Joshi [9].

In the research of S. Singh et al. [10], 5S methodology has been explained and major critical success factors for effective implementation of 5S have come out from the analysis work are file management, Team work, Safety and accidental issues. After that Ramesh et al. [11] presented an application of 5S in technology in a Bio-mass processing unit. 5S lean technology is used for attaining project diagnosing the production process, streamlining the workflow, reducing process waste, cleaning the production environment. Hasan et al. [12] also applied 5S in their research for implementing total quality management in education system of Bangladesh. Alternatively, the implementation of 5S methodology in stores department of an electrical component manufacturing industry to improve the efficiency of all processes and elimination of different loses of the company has been explained by Ankit and Patel [13]. The research work by Lamprea et al. [14] mentioned the positive effects the 5S methodology on quality, productivity, industrial safety, organizational climate of any company. The methods and techniques of 5S which are used to increase the efficiency of all processes in the industry has been described in [16]. The essential thing of this paper is to break the activities on some major steps and to maintain continuous improvement.

The research work by Agrahari et al. [15] dealt with the execution of 5S methodology in the small-scale industry which shows significant improvement in safe-ty, productivity, efficiency and housekeeping as well as stronger work ethic within the management. The research work by Patel and Thakkar [16] has approved out to apply the 5S method of lean developed to solve the difficulty of workshop with the aim of good space exploitation and exclusion of devastate in the workshop. An overview of existing works in the field of 5S in showed in this article (See in *Table 1*).

Table 1. Overview of literatures.

Topic	Research Work
5S methodology application	[1], [3], [11], [13], [15]–[17]
Theory and experimentation Lean implementation	[2], [18], [5], [19]
Effect and outcome analysis of 5S	[6]–[8], [10], [14]
Introduction of 7S	[9]

3 | Problem Statement of Manufacturing Department

A secondary manufacturing unit worker was storing the tooling in tool set away from the production process. They have described how excessive downtime was caused as tools kept mixed up in the tool set and during the shutdown process time was being wasted sorting tools and few tools go missing. Further our observations related to the situation were: frequent tool loss, presence of unnecessary item, tools are not classified thus kept together. As tools are not visual at a glance, searching time of tools kill workers valuable time which leads to waste of waiting time and waste of movement. The current situation of tool set is terrible (See in *Fig. 1*). Furthermore, purchase of new tools cause waste of transportation and expense of tools replacement is also interrelated consequence of it.

(a) (b)

Fig. 1. Current situation of tool set.

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4 | Systematic 5S Approach to the Solution

4.1 | SEIRI

Ejecting out all redundant items from the workplace which includes damaged tools, raw materials, parts, equipment, and non-comforting stock for the immediate continual operation is called sorting. Therefore, SEIRI minimizes time wastage, unnecessary movement and reduces the pitfall of the workplace. This method reduces the cost and enhance the productivity of searching and collecting items.

4.2 | SEITON

SEITON is the procedure where it always been picked the essential items that are left out after the removal of clutter as well as displayed them in an efficient man-ner. Moreover, the place of every item must be labeled for recognition and placed in a fixed location. Each tool, material, piece of equipment should be kept close to where it will be used which will reduce waiting time for total setting. In addition, error can be easily identified and corrected for which the visual control is important.

4.3 | SEISO

In this stage, a smooth-running clearing is done by removing all the clutter items and unnecessary components. This process is mostly done after the stages of sorting and set in order. During cleaning the goods/items must be in their re-quired places and the work areas must be wiped and examined regularly in order to assist improvement. Moreover, cleanliness will aid to notify the destruction caused on the equipment such as fracture, discrepancy, etc. Here, the cost of maintenance for a machine can be minimized.

4.4 | SEIKETSU

After the assembling and cleansing of the production area, it is crucial to maintain the perfect hygiene and safe environment of the workplace. Therefore, the organi-zation originate standardized procedures, rules, regularity and presumption for maintaining continuous activity in all the areas time to time. This results in an ef-fective way for implementing the tasks outlined on daily basis. Moreover, all the workers need to be involved in the process on the given workplace so that they can know their own activities.

4.2 | SHITSUKE

The proposition is to sustain clean environment as an existence process and maintaining the uniformity of work as well as standards in a systematic order. This will stimulate the participation of all workers due to consistency in '5S' ac-tivities and will lead to the improvement of 5S principles. This process declines the unorthodox and non-functioning products and increase the internal convey-ance and engagement between the workers in the organization.

The key benefits of 5S:

– *Minimization of scrap.*
– *Better usage of space for storage.*
– *Maintenance upgraded.*
– *Enhanced safety measures.*
– *Improved in production, marketability, quality and efficiency.*
– *More devoted employees.*
– *Hygienic workplace.*
– *Less risk.*
– *Enhancement of communication.*

5 | Methodology towards the Solution of the Problem

This study was done in two different steps.

5.1 | Steps of SEIRI

This is the initial step of the 5S method. SEIRI refers to classify the necessary and unnecessary tools, materials, items and remove the items which do not belong in the work area. As a result, a free up production space is created for the new business. Time level is constraint in order to find out the tools which are required. Moreover, through this method the forgotten materials detection for example spare parts and raw materials which will automatically save the reordering costs. Waste material may depreciate by identifying all the barriers and initiating ideas and improvement.

In this method, a list of question will be provided to each of the teams for the pur-pose of guiding. Here, each team will be extended over the whole work area so that the entire workspace is reviewed. The training plans will be given to the teams so that they will know what to do or not. In Addition, Red tags and Sort lists are the prime tools for SEIRI step. This is foremost to buy or make pre- numbered red tags since the number permit the matter to be tracked. Relationship between usage and frequency for listing material in showed in a tabular form (See *Table 2*).

On the other hand, safety devices have been installed properly in order to reduce hazards. In short

- *All employee's involvement in sorting and decision taken of what are needed and remove unnecessary clutter. For red tag techniques, staffs are given red tag and ask to put red tag if the tool is not needed.*
- *Remaining tools, gauges, materials, classified and then stored.*
- *Remove items which are broken, unusable or only occasionally used.*

Table 2. Relationship between usage and frequency for listing material.

Priority	Frequency of Use	How to Use
Low	Less than once per year	Throw away.
	Once per year	Store away from the workplace
Avg.	Once per month Once per week	Store together but offline
High	Once Per Day	Locate at the workplace

Here, talking with the employee, needed and unnecessary item of the manufacturing unit were investigated and found many unnecessary tools example: existing type of T Allen key set of the maker packer set, and other items were classified.

5.2 | Steps of SEITON

This is the second step of the 5S method. SEITON means "to set in order" or position everything in right place. The tools which are constantly used must be accumulated near the work area especially where they belong. Therefore, this reduces litter by storing infrequent-used tools farther away. The items are now easy to conduct by the help of this method.

The handy tools must be piled by dangling them on a tool board over a painted outline in order to recognize easily. Moreover, applying this method expand the productivity by declining the time spent fetching for inaccessible items. In addition, the cost is reduced since the last tools do not need to be re-ordered. Less hazards due to tools are kept in appropriate and ergonomic places so as a result the workers do slight twisting, bending, stretching, uplifting. Furthermore, the workstation is simpler to sterilize since the tools have been gathered in a proper place.

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Here in SEITON process we have used shadow boarding for tool standardization.

Shadow boarding Shadow boarding is an outstanding technique for setting the workspace in a well-organized manner and exploit this technique during the primary stage. This is a cooperative tool when implementing and sustaining the process of 5S. Shadow boarding layout the attributes of where the tools, equipment, supplies are stored and permit the employees to recognize from where the tools are missing. It is also commonly used when securing the equipment during travelling. This technique assists to evade losing high-priced equipment and postponed of projects.

Shadow boarding using existing furniture size of the manufacturing unit has been done. (See in *Fig. 2* and *Fig. 3*).

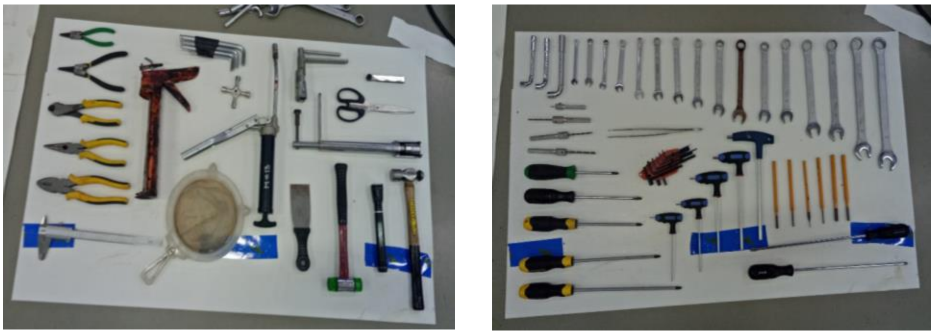

Fig. 2. Shadow boarding of 1st drawer (frequently required item) and 2nd drawer (not frequently required item).

Steps involved for shadow boarding:

I. We took classified tool from previous step and spread them in two white sheets. One for the frequently required item and other for the occasionally required item. These two sheets were of exactly same dimension of the drawer / furniture size.

II. Taking a pencil/marker all the items are traced carefully keeping required clearance in all side.

(a) **(b)**

Figure 3. Implementation of shadow boarding concept in final design and construction of the tool set (Vertical and Horizontal).

5 | Time Consumption Analysis of the Industry

According to employees of secondary manufacturing unit of the industry, a worker needs minimum of 3 tools in an hour. On the other hand, the industry incorporates 3 shift each day and 155 people work in each shift. A worker is carefully observed while searching tool from existing tooling set and further shadow board is also made to use by the same worker for this research work. Afterwards, time study shows that worker took more time while searching in existing tooling set than the shadow boarding system. A comparison of Requirement of searching time of tool in existing tooling set and shadow boarding is also done (See in *Table 3* and *Fig. 4*).

Table 3. A comparison of requirement of searching time of tool in existing tooling set and shadow boarding.

Tool	Existing Tooling Set	Shadow Boarding
Spanner	24 second	8 second
Screwdriver	18 second	5 second
Drill bit	17 second	5 second
Total time	59 second	18 second

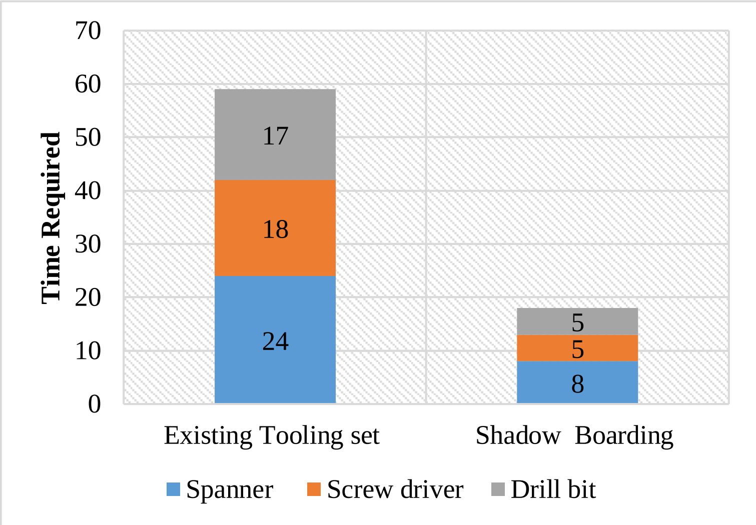

Fig. 4. A cluttered diagram showing direct comparison of time consumption study of existing tooling set and shadow boarding.

6 | Result and Discussion

Above time consumption study shows that a worker can save up to 41 second in an hour which is wasted in searching the tool in existing tooling set. Also, in every search time consumption has been lesser than the previous one. Considering all workers working in a day and searching time is reduced in each hour, time save is 152520s which is approximately 2 days. This time reduction will allow for extra productive time for employees to work meeting customer demand, being more efficient, and productive. An outcome model of shadow boarding of tooling set of manufacturing unit is outlined (See in *Fig. 5*). Ejection of all the redundant items from the workstation and keeping only the essentials documents as well as accessories in manufacturing unit has ensured effective utilization of workplace by SEIRI step of 5S. Penetrating hour of sorting raw materials, parts, tools, and document is contracted which ensured Finer economical work outflow. Backlog cost of redundant items is declined.

Alternatively, by the application of SEITON step. The required items are properly arranged which reduce the time for piercing. Location of all essential items are labelled for recognition will establish a constructive and methodical storage concept among employees and an upgrade of protection from tool missing is ensured by the step as error can be easily recognized and corrected by visual control. Implementation of shadow boarding process for designing and construction of the new tooling drawer has:

I. Improved quality as error decreases due to the calibration of time and position as well as arrangement are easily done.
II. Reduction of time as the necessary tools are stored on the shadow board so the time is preserved by not probing for tools and tackle. Moreover, shadow board is kept close to the areas of use in order for the reduction of time spent going to and from the storage areas.

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III. Minimization of safety hazards as tools and equipment are not scattered around the work areas.

IV. Loss of damage prevention as shadow boarding assign an accessible storage place for equipment, tools and supplies and as a visual aid the missing tools are clearly detected. This exercise assists to keep the items in satisfactory state.

V. Increase in productivity since the workers become well-organized and productive, therefore, they are getting more production time than before. So, the plant achieves a great profit.

VI. Accountability and traceability as shadow boarding stimulate accountability and support the process of detection losses. The visual aspect aids the customers to get back their property from the workforce since the tools are marked and it does not take such a long time in order to notify those particular items.

VII. Organized storage as shadow boarding constructs an organized storage within a definite place for definitive items. As a result, making items facile to locate when required.

5 | Conclusion

Regardless of the ease in 5S method, implementation of the system often results in failure. Not only that, but implementation barriers also lead to failures such as lack of management support, not enough time, resistance to change poor communication, the poor training and awareness of 5S.

For effective housekeeping and maintaining health and safety standards, necessity of 5S implementation is unavoidable. Elimination of unused, unwanted material from the shop floor is the main priority of 5S Sort stage to reduce clutter. Set in order aims for allocation of space for components, materials and tooling in organization results in reduction in searching time. As a result of changes, employees become self-disciplined and effects are visible in short span of time. In this paper, we have worked on the implementation of 5S in standardization of tooling set. First two steps of 5S are applied in manufacturing unit and afterwards shadow boarding execution is evaluated by time consumption study. Further outcome model of shadow boarding implementation was established from the results.

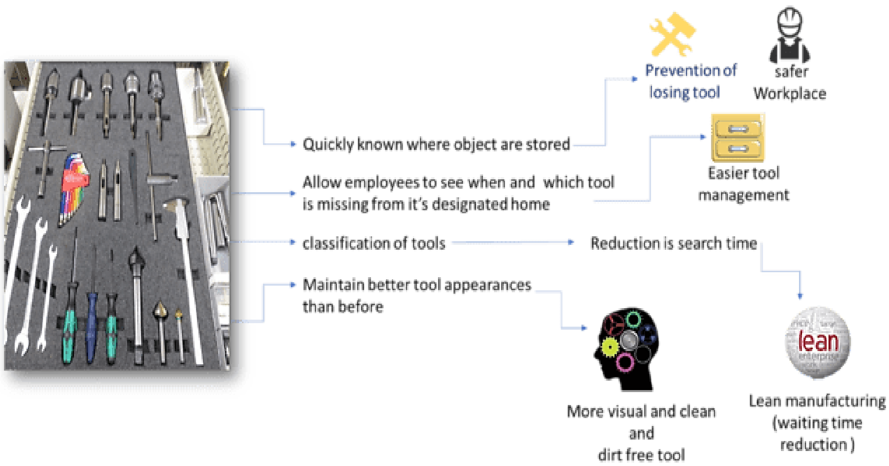

Fig. 5. Outcome model of shadow boarding of tooling set of manufacturing unit.

Future work will evaluate the methodology implementation process in other departments along with safety as the 6th S. A longitudinal study can be conducted to understand the long-term effect of changes due to 5S. The presented outcome model of 5S implementation also reveals interesting relationship between 5S and other lean tool such as 7 waste concepts. This outcome model can be examined, and performance can be evaluated.

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E-ISSN: 2717-2937 | P-ISSN: 2783-1337

International Journal of Research in Industrial Engineering

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Int. J. Res. Ind. Eng. Vol. 10, No. 4 (2021) 295–306.

Paper Type: Research Paper

Designing the Multivariate Nonconforming Proportion Control Charts Considering the Measurement Error

Seyed Mohsen Ebrahimi[1], Parisa Shahnazari-Shahrezaei[2,*]

[1] Department of Industrial Engineering, Firoozkooh Branch, Islamic Azad University, Firoozkooh, Iran; en.mohsen.ebrahimi@gmail.com.

[2] Department of Industrial Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran; parisa_shahnazari@yahoo.com.

Citation:

Ebrahimi, S. M., & Shahnazari-Shahrezaei, P. (2021). Designing the multivariate nonconforming proportion control charts considering the measurement error. *International journal of research in industrial engineering, 10* (4), 295-306.

Received: 11/09/2021 Reviewed: 12/10/2021 Revised: 13/11/2021 Accepted: 02/12/2021

Abstract

Most qualitative characteristics cannot be easily reported numerically. In such cases, each product is inspected and usually divided into two conforming and nonconforming groups based on their qualitative characteristics. Since nowadays products and processes have generally several interdependent qualitative characteristics, it is necessary to use multivariate quality control methods to make the relationship between variables and their variations. To do this, the sampling of the considered qualitative characteristic is done at the specified time intervals to check the control of the process over time after drawing the considered statistic on the control chart. A common problem while sampling is measurement error. It affects the performance of control charts, impairs their ability to detect changes in the process, and increases the cost and time to search for out-of-control situations. In this paper, the effect of measurement error on the performance of the Multivariate Nonconforming Proportion (MNP) control chart has been evaluated based on the criterion of Average Run Length (ARL) for the first time. The results imply that the measurement error has a considerable impact on the performance of this chart. Also, the results indicate that if the defective items have been wrongly considered as correct items, we would have a higher ARL compared to an ideal and accurate system. On the other hand, if the system considers right items as defective, we will have a lower ARL than the ideal and accurate system. It is proved that if both errors (considering faulty items as correct ones and vice versa) occur simultaneously, the ARL will be reduced like the previous case.

Keywords: Multivariate control chart, Measurement error, Average Run Length (ALR).

1 | Introduction

In today's world, due to the expansion of the competition field and the increase in production costs, and consumers' expectations for the quality of goods, we must always look for a workable solution to improve quality. The control charts of utility tools are in this order. As the products become more complex, it is necessary to consider the quality of the product comprehensively.

Therefore, the quality characteristic will be controlled by more than one characteristic and all the characteristics must be studied simultaneously in order to control the quality of that product properly. To do this, we have to use the information extracted from the samples taken. The measurement system includes human and measuring equipment, so this system is not 100% reliable.

Corresponding Author: parisa_shahnazari@yahoo.com

http://dx.doi.org/10.22105/riej.2021.309925.1258

In most cases, there is a difference between the observed value and the actual value of the measured parameter, known as the measurement error. On the other hand, the design of multivariate graphs in descriptive mode has not been done by considering the measurement error so far and considering the effect of the measurement error on the control chart, it is necessary to consider the measurement error in the design of this graph. Therefore, in this paper, an attempt has been made to investigate the effect of this error on the performance of the control chart of the number of defective items. The paper is organized in such a way that the second part is devoted to a review of the literature. In the third part of the control chart, the number of defective multivariate items is reviewed. In the fourth part, the control chart of the number of defective items in case of measurement error is developed. The fifth part involves solving a numerical example and analyzing its results. Finally, in the sixth section, a summary and conclusion are presented

2 | Literature Review

Today, with modern equipment for collecting information and monitoring processes, the simultaneous control of several quality characteristics is more common than one quality characteristic. For example, consider a box that can be regarded as non-compliant or defective if there is a defect in dimensions or weight. Montgomery [1] first called these processes multivariate processes. Montgomery and Mastrangelo [2] clearly showed that using univariate Shewhart control diagrams in multivariate processes would deviate from simultaneous monitoring of qualitative characteristics. Much research has been done to improve the performance of the Shewhart chart. For example, Champ and Woodall [3] have proposed the use of sensitization rules to increase the power of the graph to detect out-of-control situations. Therefore, it is necessary to use a multivariate control method to consider the internal relationships between qualitative characteristics. In addition, using a multivariate control chart is more economically and operationally cost-effective than using multiple univariate charts. Lowry and Montgomery [4] showed that typically a multivariate control scheme is more sensitive than the univariate mode to control a multivariate process. The use of multivariate control methods to monitor production processes has become increasingly popular. Like many multivariate control diagrams, the Hotelling's T-squared statistics diagram is based on a normal distribution. In the case of multivariate descriptive processes, however, the number of nonconforming units in each qualitative characteristic usually corresponds to a binomial distribution [5].

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To use control diagrams, sampling of the process must be done and the common problem in the sampling section is measurement error. Therefore, it can be said that measurement error is one of the common phenomena in the measurement system that is usually not considered and ignoring these errors can have many costs and consequences [6]. Adverse consequences of measurement error include an increase in the number of false alarms such as incorrect detection of signals out of process control and detection of delay in process change [7]. Various researchers have studied the effect of measurement error on the performance of control charts. Bennett used the $Y = X + \epsilon$ model, known as the classical measurement error model, to influence the measurement error on the performance of control charts [8]. Kanazuka [9] used the classical model to investigate the effect of measurement error on $\overline{X} - R$ control diagrams. He showed that the existence of this error reduces the power of these graphs [9]. Linna et al. [10] extended the classical model to the $Y = A + BX + \epsilon$ model. In their study, they investigated the effect of different measurement error parameters on the ARL parameter of $\overline{\mathrm{X}} - S$ and multivariate control charts and reduced the effect of error variance by using several measurements of each characteristic [10]. The effect of measurement error on the performance of weighted moving average control charts and cumulative sum control charts was evaluated by Maravelakis et al. [11]. Xiaohong and Zhaojun [12] investigated the effect of measurement error and autocorrelation on the performance of the CUSUM control chart and obtained the CUSUM control limits using the maximum likelihood method. Abbasi [13] considered the two-component measurement error and presented the model $Y_t = \alpha + \beta X_t e^{n_t} + \varepsilon_t$. He examined the performance of the EWMA diagram under the mentioned model [13].

Costa and Castagliola [14] investigated the effect of measurement error and autocorrelation on the performance of the control diagram $\overline{X}$ and showed that the performance of the control diagram is affected by measurement error and self-correlation. They improved the performance of the $\overline{X}$ control chart using multiple measurement and jump strategies. Momeni et al. [15] investigated the effect of measurement error on the control diagram $\overline{X} - R$ in fuzzy mode. Saghaei et al. [16] evaluated the design of the control diagram considering the measurement error. Amiri and Mohebbi [17] reviewed the statistical and economic design of the EWMA multi-objective control chart and in their paper examined the ARL using the Markov chain and then determined the optimal parameters of the chart with a multi-objective genetic algorithm. Noorossana and Zerehsaz [18] investigated the effect of measurement error on the performance of the EWMA control chart for monitoring profiles and showed that measurement error affects whether the process is under control or out of control. Ding and Zeng [19] also investigated the effect of measurement error on multi-stage production processes. They showed that measurement error affects the methods of estimating the regression model coefficients. For the first time, Daryabari et al. [20] investigated the effect of measurement error on the simultaneous control of the mean and variance of the process in a graph by considering the variance of the constant error with the mean time to alert criterion. They showed that the measurement error significantly affects the performance of the graph of the maximum weighted moving average and the mean squared deviations. Sabahno et al. [21] Investigated the effect of measurement error on the performance of the chi-square control chart using the VSI variable sampling distance feature. Sabahno et al. [22] Investigated the effect of measurement error on the performance of the $\overline{X}$ control chart with the VP parameter characteristic.

Table 1. Review of the literature on the subject and comparison of the characteristics of the studies.

Row	Author Names	Year Of Publication	Name Of Journal / Book	Activity Done
1	Costa and Castagliola [14]	2011	Journal of Applied Statistics	The effect of measurement error and autocorrelation on the performance of control chart $\overline{X}$ was investigated and it was shown that the performance of control chart is affected by measurement error and autocorrelation.
2	Saghaei et al. [16]	2014	International Journal of Industrial Engineering	The design of the control diagram was evaluated taking into account the measurement error.
3	Moameni et al. [15]	2012	Engineering , Technology & Applied Science Research	The effect of measurement error on control $\overline{X} - R$ diagram in fuzzy mode was investigated.
4	Amiri and Mohebbi [17]	2014	International Journal of Quality Engineering and Technology	The statistical and economic design of the EWMA multi-objective control chart was examined and the ARL was examined using the Markov chain.
5	Noorossana and Zerehsaz [18]	2015	The International Journal of Advanced Manufacturing Technology	Investigated the effect of measurement error on the performance of the EWMA control chart to monitor the profiles and showed that the measurement error will affect the performance of the chart.
6	Ding and Zeng [19]	2015	Journal of Manufacturing Systems	The effect of measurement error in multi-stage production processes was investigated which showed that measurement error affects the methods of estimating the regression model coefficients.
7	Daryabari et al. [20]	2017	Communications in Statistics-Theory and Methods	Measurement error was shown to significantly affect the performance of the MAX EWMAMS maximum moving average and the mean squared deviation.

Table 1. (Continued).

Row	Author Names	Year Of Publication	Name Of Journal / Book	Activity Done
8	Sabahno et al. [21]	2018	Quality and Reliability Engineering International	The effect of measurement error on the performance of chi-square control chart was investigated using the VSI variable sampling distance feature.
9	Sabahno et al. [22]	2018	Journal of Testing and Evaluation	The effect of measurement error on the performance of $\overline{X}$ control chart was investigated with the parameter characteristic of the VP variable.
10	Current paper			In this study, for the first time, the effect of measurement error on the performance of the multivariate control chart of the number of defective MNP items is investigated by the ARL sequence average length criterion. The results show that measurement error has affected the performance of this diagram.

3 | Multivariate Control Diagram

Most qualitative characteristics cannot be easily reported numerically. In such cases, each inspected product is usually divided into two groups, compliant and non-compliant with the desired quality characteristics. The statistical principles of non-conforming item ratio control charts are based on binomial distribution. Assume that m has a qualitative characteristic and p_i represents the non-conformance ratio of a qualitative characteristic and c_i represents the number of nonconformities in the qualitative characteristic i. The correlation coefficient between qualitative characteristic i and qualitative characteristic j is considered as δ_{ij} [23].

To draw MNP graphs, we need to calculate and draw a statistic called X, which is calculated as the mean and variance as follows [3]:

$$X=\sum_{i=1}^{m}\frac{c_i}{\sqrt{p_i}}, \quad E(X)= n\sum_{j=1}^{m}\sqrt{p_j}, \quad Var(x)=n\left\{\sum_{j=1}^{m}\left(1-p_j\right)+2\sum_{i<j}\delta_{ij}\sqrt{(1-p_i)(1-p_j)}\right\}. \tag{1}$$

Using the general principles of control charts, the control limits in MNP charts are obtained according to the following equation [3]:

$$\begin{cases} UCL = n\sum_{j=1}^{3}\sqrt{\bar{p}_j}+3\sqrt{n\left\{\sum_{j=1}^{m}(1-p_j)+2\sum_{i<j}(\delta ij\sqrt{(1-p_i)\,(1-p_j)}\right\}}, \\ CL = n\sum_{j=1}^{m}\sqrt{\bar{p}_j}\ , \\ LCL = n\sum_{j=1}^{3}\sqrt{\bar{p}_j}-3\sqrt{n\left\{\sum_{j=1}^{m}(1-p_j)+2\sum_{i<j}(\delta ij\sqrt{(1-p_i)\,(1-p_j)}\right\}}. \end{cases} \tag{2}$$

4 | MNP Control Chart Considering Measurement Error

4.1 | Parameters and Sets

c_j: Number of non-conformances in sample i.

p_j: Probability of non-conformance due to qualitative characteristic j.

p_i: Probability of non-conformance due to qualitative feature i.

μ_i: Average of sample i.

δ_{ij}: Standard deviation of ith sample.

P_{ej}: Probability of non-compliance in the presence of a measurement characteristic of a qualitative characteristic j.

4.2 | Conditional Bernoulli Error and Distribution

In practice, inspectors may commit two types of inspection errors during the inspection operation. In order to investigate such a situation, the following events are considered.

A_1: The event is that a product is really defective.

A_2: The event is that a product is really intact.

B: The event is that a product is considered defective during an inspection.

$B|A_2$: The event is that a healthy product is considered a defective product.

$B^c|A_1$: The event is that a defective product is considered an intact product.

Assume that P_j and P_{ej} are the proportions of actual and unreal defective items in the accumulations of products, respectively. Then $P_j = p\,(A_1)$ and $P_{ej} = p(B)$.

Also, suppose $e_1 = (B|A2)$ and $e_2 = (B^c/A1)$ are equal to the probability of classifying an intact product as a defective product and a defective product as an intact product, respectively. As a result, according to the law of total probability, we have:

$$P_{ej} = p\left(A_1\right)\,p\left(B\middle|A_1\right) + p\left(A_2\right)\,p\left(B\middle|A_2\right) = P_j\left(1 - e_2\right) + (1 - P_j)e_1, \tag{3}$$

$$\begin{cases} UCL = n \sum_{j=1}^{3} \sqrt{P_{ej}} + 3\sqrt{n\left\{\sum_{j=1}^{m}(1-P_{ej}) + 2\sum_{i<j}(\delta_{ij}\sqrt{(1-P_{ej})(1-P_{ej})}\right\}}, \\ CL = n\sum_{j=1}^{m}\sqrt{P_{ej}}, \\ LCL = n \sum_{j=1}^{3} \sqrt{P_{ej}} - 3\sqrt{n\left\{\sum_{j=1}^{m}(1-P_{ej}) + 2\sum_{i<j}(\delta_{ij}\sqrt{(1-P_{ej})(1-P_{ej})}\right\}}. \end{cases}$$

4.3 | MNP Chart Control Interval Considering Measurement Error

Eq. (2) is used to calculate the control limits in MNP diagrams. Due to the inspection error, P_j will no longer be obtained directly, and this value can be calculated from the following probability relation, and instead of P_j, we will use P_{ej} in all relations:

$$P_{ej} = P_j * (1 - e_2) + (1 - P_j) * e_1. \tag{4}$$

4.4 | MNP Control Chart Statistics Considering Measurement Error

The statistics of the multivariate control chart of the number of defective items in case of measurement error is as follows:

$$X=\sum_{j=1}^{m}\frac{c_j}{\sqrt{p_{ej}}}, \quad E(X)= n\sum_{j=1}^{m}\sqrt{P_{ej}},$$

$$Var(x)=n\left\{\sum_{j=1}^{m}(1-P_{ej}) + 2\sum_{i<j}\delta_{ij}\sqrt{(1-p_{ei})(1-P_{ej})}\right\}. \tag{5}$$

5 | Effect of Measurement Error on the Performance of the Control Chart of the Number of Defective Multivariate MNP Items

Checking the performance of the control chart the samples taken are measured by the ARL to achieve an out-of-control warning. To calculate this important and effective index, MATLAB simulation software has been used, which allows us to simulate our desired conditions by coding. To investigate the effect of the error in the MNP control diagram, because the type of inspections is descriptive and qualitative, we encounter a conditional Bernoulli distribution according to *Eq. (3)*. In order to be able to calculate the ARL index and use it to analyze the results, in the first step we need to calculate some of the parameters used in the formula. As mentioned before, in the case of measurement error in the preparation of MNP diagrams, instead of the p_j parameter, we encounter the p_{ej} parameter, which we will need to determine the effective factors in this regard.

In *Table 2*, different values of p_j, e_1 and e_2 are considered. Once the mentioned values are known, other required parameters can be calculated and by entering the necessary parameters in MATLAB software, we can calculate the ARL value for different values.

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Table 2. Results for ARL (average sequence length) for different values of p_j, e_1 and e_2 .

Assumptions																				
ARL0 =452.3843, P(P1=.0533, P2=.0933,P3=.1367), e1=good Item is classified bad, P1=P1+Delta, Delta=.01, e2= Bad Item is classified Good																				
			P=0.0733		**P=0.15**		**P=0.2**		**p=0.25**		**p=0.3**		**0.35**		**p=0.4**		**p=0.45**		**p=0.50**	
Error type	**e1**	**e2**	**ARL Error**	**ARL No Error**	**ARL Error**	**ARL No Error**	**ARL Error**	**ARL No Error**	**ARL Error**	**ARL No Error**	**ARL Error**	**ARL No Error**	**ARL Error**	**ARL No Error**	**ARL Error**	**ARL No Error**	**ARL Error**	**ARL No Error**	**ARL Error**	**ARL No Error**
Part One (Only Type I Error)	0.02	0	130.28	295.85	44.83	92.48	25.81	49.84	14.65	31.51	11.65	20.54	8.46	13.87	6.38	10.2	5	7.49	3.92	5.84
	0.05	0	41.51	295.85	17.99	92.48	11.73	49.84	8.31	31.51	5.92	20.54	4.65	13.87	3.68	10.2	3.02	7.49	2.51	5.84
	0.1	0	9.84	295.85	5.54	92.48	4.15	49.84	3.27	31.51	2.63	20.54	2.21	13.87	1.91	10.2	1.67	7.49	1.5	5.84
	0.15	0	3.52	295.85	2.45	92.48	2.06	49.84	1.8	31.51	1.58	20.54	1.43	13.87	1.32	10.2	1.23	7.49	1.17	5.84
	0.2	0	1.81	295.85	1.5	92.48	1.36	49.84	1.27	31.51	1.19	20.54	1.14	13.87	1.1	10.2	1.07	7.49	1.05	5.84
	0.25	0	1.26	295.85	1.17	92.48	1.11	49.84	1.08	31.51	1.05	20.54	1.03	13.87	1.02	10.2	1.01	7.49	1.01	5.84
Part II (only the second type of error)	0	0.02	335.96	295.85	103.33	92.48	56.61	49.84	34.63	31.51	22.24	20.54	15.4	13.87	11.24	10.2	8.4	7.49	6.41	5.84
	0	0.05	373.39	295.85	120.41	92.48	67.5	49.84	41.16	31.51	26.96	20.54	18.3	13.87	13.09	10.2	9.7	7.49	7.57	5.84
	0	0.1	460.95	295.85	159.62	92.48	88.91	49.84	55.04	31.51	35.54	20.54	23.86	13.87	17.77	10.2	12.92	7.49	9.89	5.84
	0	0.15	530.59	295.85	217.06	92.48	118.67	49.84	73.94	31.51	48.52	20.54	33.14	13.87	23.88	10.2	17.52	7.49	13.15	5.84
	0	0.2	536.01	295.85	288.84	92.48	163.95	49.84	103.14	31.51	66.87	20.54	45.03	13.87	32.57	10.2	24.16	7.49	18.27	5.84
	0	0.25	541.6	295.85	395.32	92.48	229.14	49.84	146.5	31.51	96.32	20.54	63.95	13.87	45.6	10.2	33.73	7.49	25.53	5.84
Part III (Existence of the first and second type of	0.02	0.02	414.22	295.85	49.05	92.48	28.82	49.84	18.9	31.51	12.99	20.54	9.39	13.87	6.95	10.2	5.37	7.49	4.31	5.84
	0.05	0.05	50.56	295.85	21.96	92.48	13.96	49.84	9.85	31.51	7.28	20.54	5.5	13.87	4.39	10.2	3.61	7.49	2.93	5.84
	0.1	0.1	12.97	295.85	7.6	92.48	5.62	49.84	4.31	31.51	3.55	20.54	2.87	13.87	2.45	10.2	2.15	7.49	1.9	5.84
	0.15	0.15	4.82	295.85	3.31	92.48	2.78	49.84	2.41	31.51	2.07	20.54	1.83	13.87	1.65	10.2	1.53	7.49	1.41	5.84
	0.2	0.2	2.35	295.85	1.98	92.48	1.76	49.84	1.59	31.51	1.48	20.54	1.37	13.87	1.31	10.2	1.24	7.49	1.18	5.84
	0.25	0.25	1.51	295.85	1.35	92.48	1.32	49.84	1.26	31.51	1.19	20.54	1.17	13.87	1.12	10.2	1.1	7.49	1.08	5.84

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5.1 | General Results of Reviewing the Results of the Tables

As can be seen in *Table 2*, each section has its own assumptions in different parameters, which consist of three Sections 1, 2 and 3.

In Section 1 of *Table 2*, the error-free mode has a higher ARL than the error mode, which means that the system will need more repetitions to announce the first out-of-control warning in error-free mode. In Section 2, for different p_j values, the error-free state has less ARL than the error state, which means that the system will need fewer repetitions to issue the first out-of-control warning. This is because it treats defective items as healthy items and the system crashes. In Section 3, different states can occur due to the existence of different values for the errors e_1 and e_2, depending on the degree of influence of the relationship of the values e_1 and e_2 , we see different behaviors.

In Section 1, we only have the error e_1 (considering the intact item as a defective item) and by increasing the values of e_1, the ARL values decrease, which means the number of times it takes for the alarm system to go out of control is reduced. This is because the system treats intact items as defective items. *Fig. 1* shows the ARL values for $p = 0.5$ in the error and no error mode.

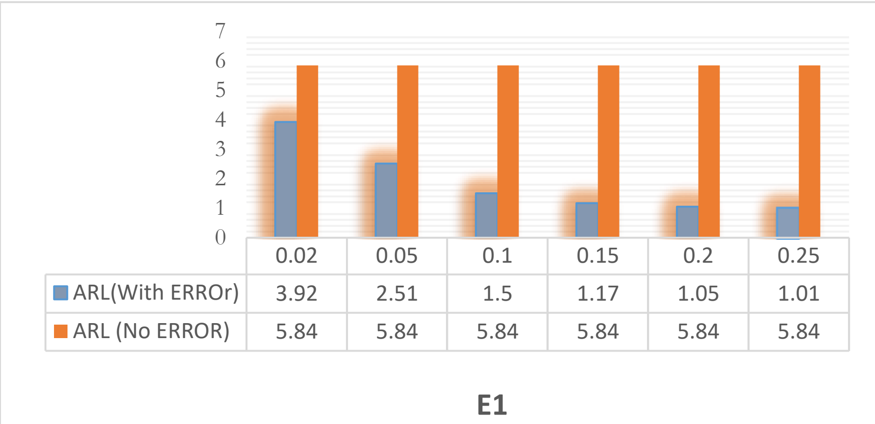


Fig. 1. ARL comparison diagram with error and no error for constant value P = 0.5.

In Section 2, we only have the error e_2 (considering the defective item as a healthy item) and as the values of e_2 increase, the ARL values also increase, which is why This means that the number of times it takes for the alarm system to go out of control increases. *Fig. 2* shows the ARL values for p = 0.0733 in the error and no error mode.

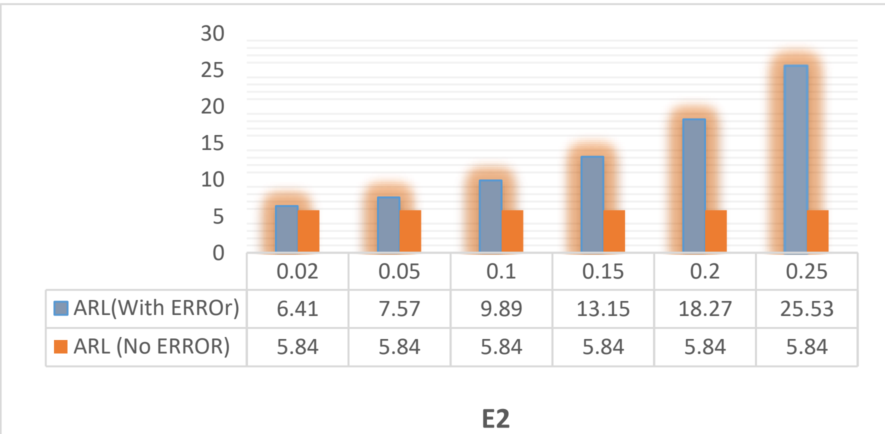


Fig. 2. ARL comparison diagram in error and no error mode for constant value P = 0.0733.

In Section 3, we have both the error e_1 and the error e_2, the values of both of which are considered the same because the necessary computational cases are not large and wide, and the value ARL decreases with increasing error rates e_1 and e_2. This means that the out-of-control mode is quickly detected due to a measurement error and the system alert is activated. *Fig. 3* shows the ARL values for $E_2 = E_1 = 0.05$ in the error and non-error mode.

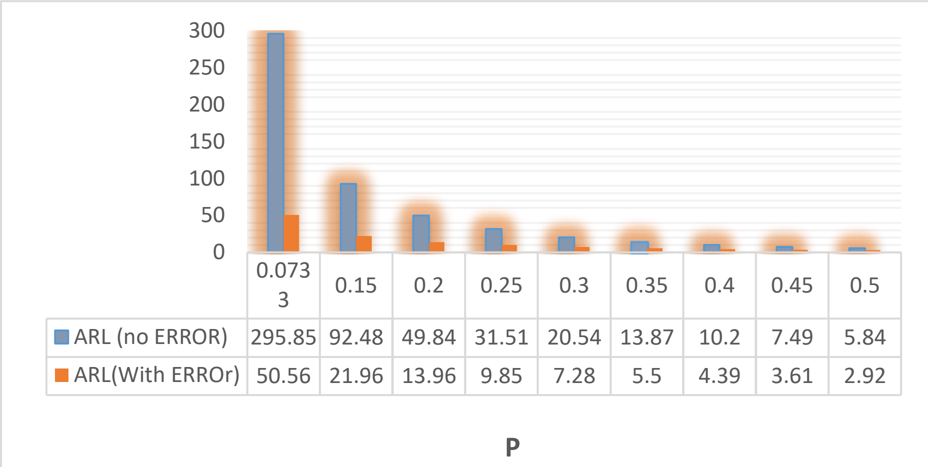


Fig. 3. ARL comparison diagram with error and no error for constant value $E_1 = E_2 = 0.05$.

By changing and increasing the value of p_1 (from $p = 0.0733$ to $p = 0.5$) and increasing the error in different parts, in Sections 1 and 3 of *Table 2*, we see a decrease in ARL and in Section 2 in each section with increasing error we see an increase in ARL. And with increasing the value of p (from p = 0.0733 to p = 0.5) ARL has a decreasing trend.

5.2 | Partial Analysis of Tables

Impact of error e_2, when the ratio of defective process items is almost small, it has a greater effect on the performance of the control graph than large p-cases. For example, consider the case: $p = 0.0733$, $e_2 = 0.02$ and $p = 0.5$, $e_2 = 0.15$ (percentage of error $\frac{e_2}{p}$ is approximately equal with 30%). The difference between ARL in error-free and error-free mode is 40.11 and 7.31, respectively. In other words, the higher the p, the higher the error e_2, even if we increase the error rate by the same ratio $\frac{e_2}{p}$.

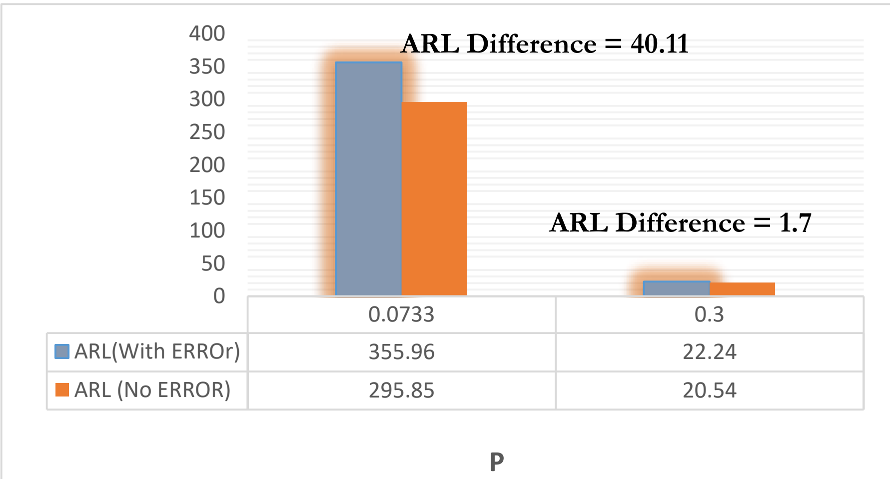


Fig. 4. Comparison diagram of ARL difference with error and no error for constant value $e_2 = 0.02$.

As the error e_2 increases, the ARL increases and the control chart warns later. By increasing p and the error e_2 being the same, the effect of this error can be ignored. For example, as shown in *Fig. 4*, when $e_2 = 0.02, p = 0.0733$ i.e., $\frac{0.02}{0.0733} = \%27$, the rate is ARL = 40.11 and when $e_2 = 0.02, p = 0.3$, i.e., $\frac{0.02}{0.3} = 6\%$, ARL = 1.7 and decreases to 38.41, the effect of this error on the performance of the control chart can be ignored.

As e_1 increases, the proportion of defective items p increases, and the control chart warns earlier than the error-free state. The higher the e_1 value, the lower the ARL and the faster the change can be detected. For example, consider $e_1 = .02, p = 0.0733$ and $e_1 = 0.25, p = .0733$ARL is equal to: 130.28 and 1.26, respectively.

The effect of error e_1 and e_2 for the same values are not equal to each other, and error e_1 has a greater effect on performance than error e_2 The chart will have control. For example, consider $e_1 = 0.02, p = 0.0733$ and $e_2 = 0.02, p = 0.0733$. The state difference (error-free) with ARL is 40.11 and 165.57, respectively, which indicates this.

The effect of error e_1 , when the proportion of defective items in the process is relatively small, it has a greater effect on the performance of the control graph than in the case of large ps, as shown in *Fig. 5*. Compared to $p = 0.5$, it has a larger numerical value.

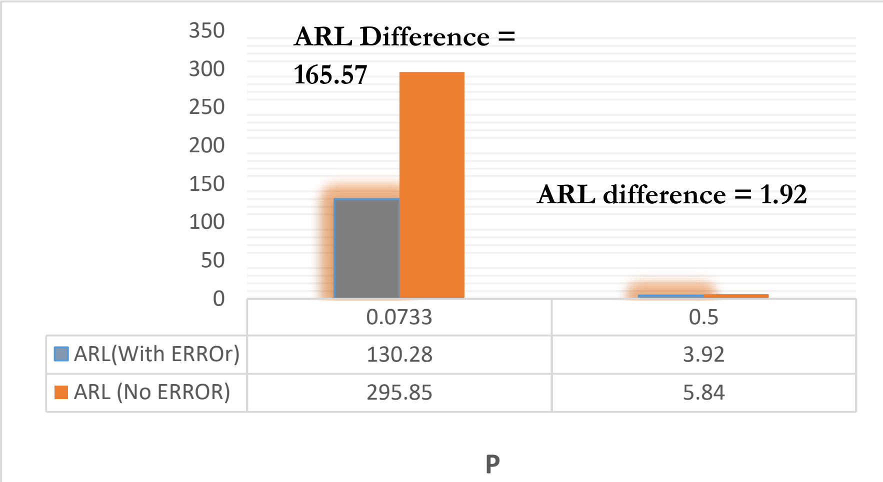
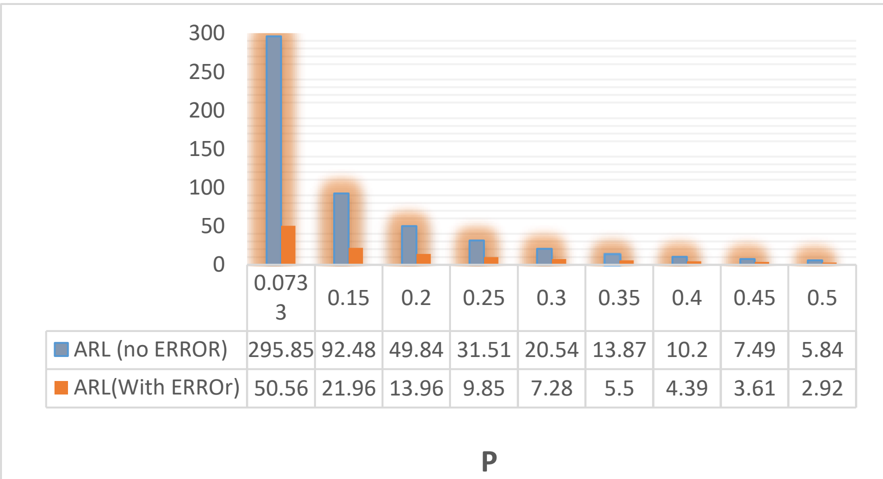


Fig. 5. Comparison diagram of ARL difference with error and no error for constant value $e_1 = 0.02$.

When we have the error e_1 and e_2 at the same time and with the same size, the performance of the graph is almost the same as when we have only the error e_1 . The reason for this is that the error e_2 has little effect on the performance of the control chart, especially at *p*s greater than 0.0733, and the greatest effect is due to the error e_1 . For example, according to *Fig. 6 (a)* and *(b)*, when p =0.15 and $e_1 = e_2 = 0.05$, the difference is ARL = 70.52 and when we have only the error e_1 and $e_1 = 0.05$, the difference is ARL = 74.49 which are slightly different from each other and almost equal.



(a)

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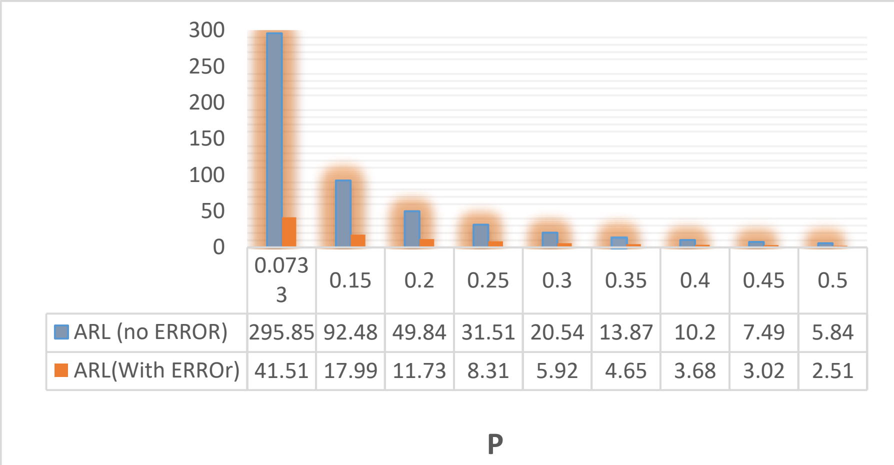

(b)

Fig. 6. Comparison of the state diagram of having both types of errors with the cases having only the error of the first type.

5 | Conclusion

Measurement error is one of the common phenomena in the measurement system that is usually not considered and ignoring this error can have many costs and consequences. Adverse consequences of measurement error include an increase in the number of false alarms, such as incorrect detection of out-of-process signals and delayed detection of changes in the process. This is not consistent with the goal of statistical quality control, which is to identify deviations as soon as possible. Therefore, considering the measurement error in designing multivariate control diagrams is of great importance. In this paper, for the first time, the effect of measurement error on the performance of the MNP control chart was investigated by the ARL criterion. The results show that measurement error affects the performance of this diagram. If the measurement system mistakenly counts only defective items as healthy items, we have an average time to the first warning more than ideally and without system error. On the other hand, if the system mistakenly counts only healthy items as defective items, we will have an average time to the first warning less than ideally and without system error. Also, if both errors occur simultaneously (counting defective items as healthy items and vice versa), the system will behave differently depending on the amount of each error, while the values of both errors are considered the same. It can only be said that as the amount of error increases and the shift increases the probability of the number of defective items decreases, the ARL will decrease. Designing other control charts to monitor processes in the presence of measurement error can be considered as a topic for future studies.

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Shahnazari-Shahrezaei and Ebrahimi | Int. J. Res. Ind. Eng. 10(4) (2021) 295-306

E-ISSN: 2717-2937 | P-ISSN: 2783-1337

International Journal of Research in Industrial Engineering

IJRIE

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Int. J. Res. Ind. Eng. Vol. 10, No. 4 (2021) 307–317.

Paper Type: Research Paper

Supply Chain Management Information System Model for Quality Assurance in Educational Management for ASEAN University Network Quality Assurance (AUN-QA)

Artaphon Chansamut*

Rajamangala University of Technology Krungthep, Bangkok, Thailand; artaphon.c@mail.rmutk.ac.th.

Citation:

Chansamut, A. (2021). Supply chain management information system model for quality assurance in educational management for ASEAN University network quality assurance (AUN-QA). *International journal of research in industrial engineering, 10* (4), 307-317.

Received: 30/06/2021 Reviewed: 12/08/2021 Revised: 05/11/2021 Accept: 23/11/2021

Abstract

The research aims to design and to assess the suitability supply chain management information system model for quality assurance in educational management for ASEAN University Network Quality Assurance (AUN-QA). The samples are 15 experts selected by purposive sampling. The data is analyzed by means and standardized deviations statistically. The research result shows that supply chain management information system model for quality assurance in educational management for AUN-QA is consisted of 5 keys which are main components, suppliers, manufacturer, customer, consumers. The data is analyzed by using arithmetic mean and standard deviation. The assessment of supply chain management information system model for quality assurance in educational management for AUN-QA. The results showed that the model was validated at a "high" level, suggesting that supply chain management information system model for quality assurance in educational management for AUN-QA aims to support sustainable information system development.

Keywords: Supply chain management, Information system model, Quality assurance in educational management, AUN-QA.

1 | Introduction

Education system is the process whereby individuals acquire knowledge and other qualifications that promote their social survival. Therefore, a consideration of education quality should be based on educational goals, e.g., qualifications of graduates, which should include knowledge, skills and other characteristics as prescribed by the curricula. Since testifying these qualifications requires time, and good effective sustainable administrative management, it is important to assure guardians, stakeholders and other involved parties that students who are graduated from a particular institution will be decent, competent and happy in society and take part in social development that progresses in line with the pace of globalization. To answer all the questions of education quality, it should be set up as principles or elements which a comparison can be made to inform development, supervision, examination and assessment of quality. Therefore, the standards of higher education, and student education as announced herein, are the requirements of education quality for all higher education institutions and student educations to utilize as goals or a directional framework to develop

Corresponding Author: artaphon.c@mail.rmutk.ac.th

http://dx.doi.org/10.22105/riej.2021.293034.1231

sustainable quality of the institutions, and to use in self-assessment every year, or for a specified period of time, in order to learn whether educational administration has achieved its goals. These standards are also important for educational service areas or host units to employ as goals in supervision, examination and assessment of quality as a whole to inform quality improvement planning [1] and [8]. The awareness of the supply chain management information system model for quality assurance can be practical as a method to accomplish work procedures, actions and affairs within the organization. It starts from planning, providing accurate information at the time of need, practicing and maintenance, distribution or destruction by giving priority to information exchange, data analysis and sharing in order to achieve productivity through the development. The nature of supply chain and information technology will be derived to play a role in changing work processes to be more computerized in order to style occupied custom of technology not only carrying supply chain and information technology to work but also be able to determine the organization inevitably. Supply chain and information technology is increasing work proficiency, diminish work period, and costs are the heart of the progression organization about supply chain and information technology. Useful strategy and evidence technology are attaching with the work experience of staffs complicated in the supervision of quality assurance work with an incorporated work process to increase work competence and generate additional value for the association to continue the quality and standard of education in higher education. It is very important at the progress level. The ASEAN Quality Assurance Network (AUN-QA) is an ASEAN university network that is a collaboration of higher education institutes between member countries consisting of the National Association of East Asia, South Chiang Mai or ASEAN with the aim of establishing to promote educational cooperation which is an essential mechanism for creating a foundation for society and regional unity. The model for quality assurance can be practical as a method or tactic for dealing with quality assurance to accomplish work procedures, actions and affairs within the organization. It starts from planning, providing accurate information at the time of need, thus the researchers had an idea to develop supply chain management information system model for quality assurance in education management for AUN-QA.

2 | Literature Review

2.1 | Information and Supply Chain According to Asean University Network Quality Assurnace at Programme Level

Chansamut [4] said that the article, relationship between information and supply chain according to asean university network quality assurnace at programme level AUN-QA at programme level) importance

for applying in actual work settings. Based on findings from literature review, the researcher found a large number of papers and articles in supply chain. The relationship between information and supply is a key process to support the education whole activities system from upstream suppliers to downstream consumers. It enables the organization to promptly check the supply chain and information technology to ensure that the organization operates smoothly and effectively based on the determined strategies. The processconsisted of suppliers, manufacturer customers, including 11 activities in the supply chain namely, 1) Expected Learning Outcomes, 2(Programme Specification, 3(Programme Structure and Content, 4(Teaching and Learning Strategy, 5(Student Assessment, 6(Academic Staff Quality, 7(Support Staff Quality, 8(Student Quality and Support, 9) Facilities and Infrastructure, 10(Quality Enhancement, and 11(Output. All activities are connected with information communication technology in the educational institute according to asana university network quality assurance at programme level (AUN-QA at programme Level) start from the creation of information, news and resources to apply together to move the goods from the supplier to the customer, resulting in a rapid flow of information and effectively. This truly added the educational institute value as the production satisfactory for the consumers.

2.2 | Quality Assurance

Quality assurance is the process of determining the quality standards of education and the assessment process to meet the educational quality standards [10]. Internal quality assurance refers to guidelines for assessing the quality of education within the university mission, as graduate production including academic research, academic services, preservation of arts that educational quality assurance can be used to describe all activities and mechanisms which related to quality, both at the system level and the level of teaching in higher education institutions

2.3 | Quality Assurance of ASEAN University Network (AUN-QA)

AUN-QA criteria define a curriculum development based on AUN-QA criteria indicating that the department must follow teaching strategies and evaluation of quality indicators. To improve the program, it should have a course map showing the balance proportion of content, skills and courses along with expert that expected to learning outcomes and to use teaching approaches interrelated to innumerable assessment methods [14]. AUN-QA criteria are the presence of a university that is a property of a vast country, and it has a strategic plan in efforts to improve the quality and competitiveness of the country. Consequently, it is necessary to attempt the strength and increase the role as well as a role in the future.

Supply Chain and Information system is one of the goals that all education institutions strive to achieve. Supply Chain and Information will help education institutions improve efficiency and produce high-caliber graduates who have all the required characteristics.

3 | Conceptual Framework

This research's framework consists analysis and synthesis of documents supply chain management information system model for quality assurance in educational management for asean AUN- QA and the assessment the suitability of the model, as detailed in *Fig 1*.

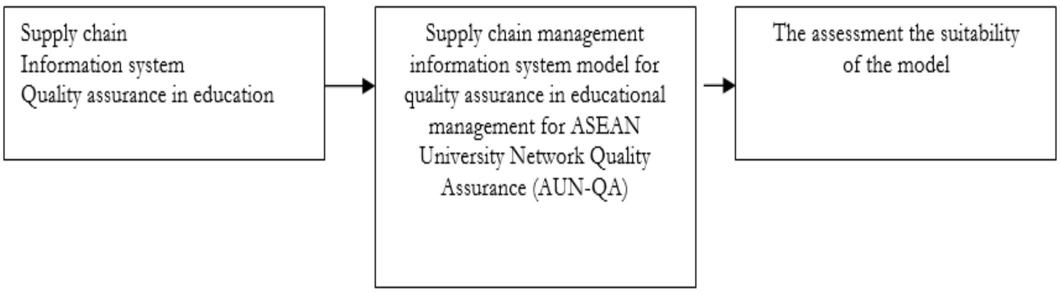

Fig. 1. Conceptual framework about Supply chain management information system model for quality assurance in educational management for AUN-QA.

3.1 | Research Hypothesis

Supply chain management information system model for quality assurance in educational management for AUN-QA is evaluated to be appropriate at the high level.

3.2 | Research Instruments

A questionnaire to assess the expert's opinions toward the supply chain management information system model for quality assurance in educational management for AUN-QA is evaluated to be appropriate at the high level.

3.3 | Research Scope

Population: The population of this study consisted of 5 experts on supply chain management, 5 experts on quality assurance in education and 5 experts on information technology system.

Samples: These experts were chosen by the method of purposive sampling of individuals who have more than four years of work experience.

Variable of research: The independent variable is supply chain management information system model for quality assurance in educational management for AUN- QA.

The dependent variable is the evaluation result of supply chain management information system model for quality assurance in educational management for AUN- QA.

4 | Research Methodology

Supply chain management information system model for quality assurance in educational management for AUN-QA is the following:

- *Study and analyse the relevant documents and research on model of the supply chain management information system model for quality assurance in educational management for AUN-QA.*
- *Use the obtained data to establish the conceptual frameworks for supply chain management information system model for quality assurance in educational management for AUN-QA.*
- *Present the model of supply chain management information system model for quality assurance in educational management for AUN-QA to the advisor for revision and amendment.*
- *Create questionnaire for evaluating the suitability of the model of supply chain management information system model for quality assurance in educational management for AUN-QA namely main components, suppliers, manufacturer, customer, consumers.*

The developed questionnaire was a 5-scale rating questionnaire, with interpreted meanings as follows:

- *The rating of 5 means most appropriate.*
- *The rating of 4 means highly appropriate.*
- *The rating of 3 means moderately appropriate.*
- *The rating of 2 means lowly appropriate.*
- *The rating of 1 means least appropriate.*

Data collection and analysis. The developed questionnaire was sent to the experts in order to ask their opinions on appropriateness of developed model. Responses from the experts were analyzed to find the mean and standard deviation of each component. Criteria for interpretation of the means are as follows: [2], [3], [4], [5] and [6].

- *The rating means ranging from 4.51 – 5.00 means appropriate at the highest level.*
- *The rating means ranging from 3.51 – 4.50 means appropriate at the high level.*
- *The rating means ranging from 2.51 – 3.50 means appropriate at the moderate level.*
- *The rating means ranging from 1.51 – 2.50 means appropriate at the low level.*
- *The rating means ranging from 0.00 – 1.50 means appropriate at the lowest*

Final improvement of the developed model on advice from the experts.

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5 | Research Results

Results of the research are presented in *Fig. 1*.

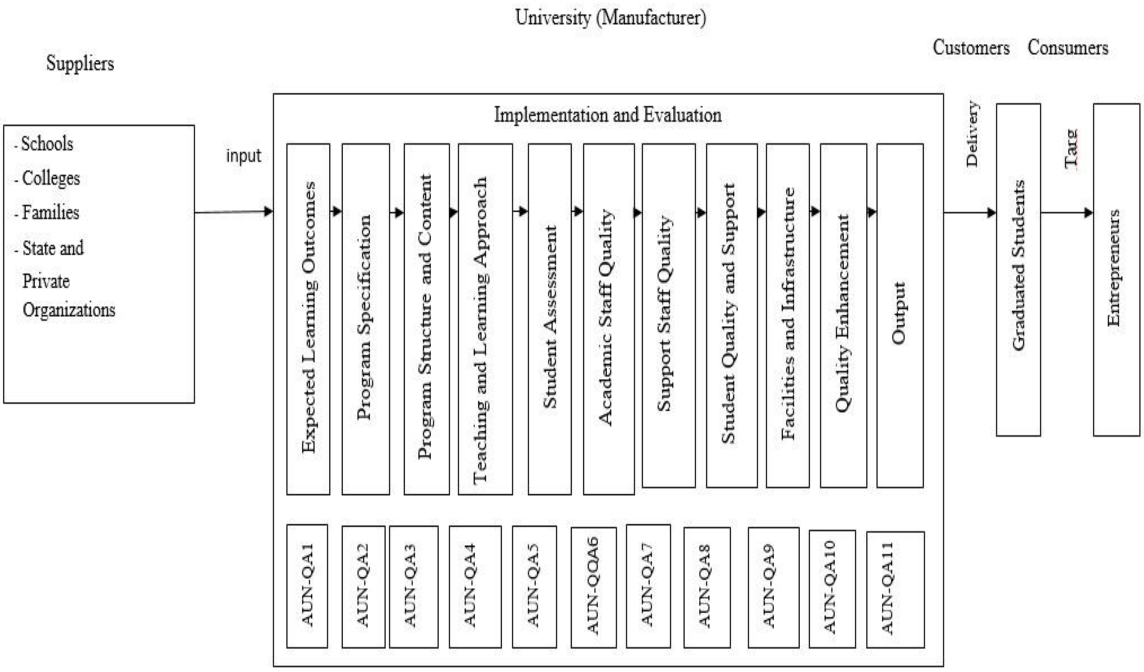

Fig. 2. Supply chain management information system model for quality assurance in educational management for AUN-QA.

Table 1. Suppliers, with its stakeholders, activities, and needs for information.

Suppliers	Activities	Needs for Information
Stakeholders: 1. School 2. College 3. Family 4. State and Private Organizations	- Sending graduated high school students. - Sending self-supported students. - Giving funding support for study. - Giving educational scholarships.	To reduce time in the admission process, with quick responses.

5.1 | The Principle of the Supply Chain Management Information System Model

Suppliers: Suppliers of the student (High school/college), Supplies of the family (Parents, Siblings), relatives, etc. and Government and private organizations (Scholarship). The suppliers mean the organizations that supply raw materials to the manufacturer. Raw materials in this case are students who graduated from high schools or two-year colleges, or students who receive special quotas for admission. They can apply for admission via the computer system that can process and store the data systematically.

Table 2. University (manufacturer) with its steps of quality assurance in educational implementation and evaluation, activities, and needs for information.

University (Manufacturer)	Activities	Needs for Information
Steps of quality assurance in educational Implementation and evaluation: 1. Expected Learning Outcomes (AUN-QA 1)	-The expected learning outcomes have been clearly formulated and aligned with the vision and mission of the university. -The expected learning outcomes cover both subject specific and generic (i.e. transferable) learning outcome. -The expected learning outcomes clearly reflect the requirements of the stakeholders.	- To be filed and stored systematically to prevent the loss of information.
2. Programme Specification (AUN-QA 2)	-The information in the programme specification is comprehensive and up-to-date. -The information in the course specification is comprehensive and up-to-date. -The programme and course specifications are communicated and made available to the stakeholders.	- To eliminate overlapping and duplicating work performances.
3. Programme Structure and Content (AUN-QA 3)	-The curriculum is designed based on constructive alignment with the expected learning outcome. -The contribution made by each course to achieve the expected learning outcomes is clear. -The curriculum is logically structured, sequenced, integrated and up-to-date.	- Accurate evaluation information.
4. Teaching and Learning Approach (AUN-QA 4)	-The educational philosophy is well articulated and communicated to all stakeholders. -Teaching and learning activities are constructively aligned to the achievement of the expected learning outcomes. -Teaching and learning activities enhance life-long learning.	-Complete evaluation reports.
5.Student Assessment (AUN-QA 5)	-The student assessment is constructively aligned to the achievement of the expected learning outcomes. -The student assessments including timelines, methods, regulations, weight distribution, rubrics and grading are explicit and communicated to students. -Methods including assessment rubrics and marking schemes are used to ensure validity, reliability and fairness of student assessment. -Students have ready access to appeal procedure. - Feedback of student assessment is timely and helps to improve learning.	- Speedy reports.

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Table 2. (Continued).

University (Manufacturer)	Activities	Needs for Information
6. Academic Staff Quality (AUN-QA 6)	-Academic staff planning (considering succession, promotion, re-deployment, termination, and retirement) is carried out to fulfil the needs for education, research and service. -Staff-to-student ratio and workload are measured and monitored to improve the quality of education, research and service. -Recruitment and selection criteria including ethics and academic freedom for appointment, deployment and promotion are determined and communicated. -Competences of academic staff are identified and evaluated. -Training and developmental needs of academic staff are identified and activities are implemented to fulfil them.	- Speedy reports.
7. Support Staff Quality (AUN-QA 7)	-Performance management including rewards and recognition is implemented to motivate and support education, research and service. -The types and quantity of research activities by academic staff are established, monitored and benchmarked for improvement. -Support staff planning (at the library, laboratory, IT facility and student services) is carried out to fulfil the needs for education, research and service. -Recruitment and selection criteria for appointment, deployment and promotion are determined and communicated. -Competences of support staff are identified and evaluated. Training and developmental needs of support staff are identified and activities are implemented to fulfil them. -Performance management including rewards and recognition is implemented to motivate and support education, research and service.	- Up-to-date evaluation reports.
8. Student Quality and Support (AUN-QA 8)	-The student intake policy and admission criteria are defined, communicated, published, and up-to date. -The methods and criteria for the selection of students are determined and evaluated. -There is an adequate monitoring system for student progress, academic performance, and workload.	- Speedy reports.

Table 2. (Continued).

University (Manufacturer)	Activities	Needs for Information
8. Student Quality and Support (AUN-QA 8)	-Academic advice, co-curricular activities, student competition, and other student support services are available to improve learning and employability. -The physical, social and psychological environment is conducive for education and research as well as personal well-being.	- Speedy reports.
9. Facilities and Infrastructure (AUN-QA 9)	-The teaching and learning facilities and equipment (lecture halls, classrooms, project rooms, etc.) are adequate and updated to support education and research. - The library and its resources are adequate and updated to support education and research. -The IT facilities including e-learning infrastructure are adequate and updated to support education and research. -The standards for environment, health and safety; and access for people with special needs are defined and implemented.	- Complete evaluation reports.
10. Quality Enhancement (AUN-QA 10)	-Stakeholders' needs and feedback serve as input to curriculum design and development. -The curriculum design and development process are established and subjected to evaluation and enhancement. -The teaching and learning processes and student assessment are continuously reviewed and evaluated to evaluation and enhancement.	-Speedy reports.
10. Quality Enhancement (AUN-QA 10)	-Quality of support services and facilities (at the library, laboratory, IT facility and student services) is subjected to evaluation and enhancement. -The stakeholder's feedback mechanisms are systematic and subjected to evaluation and enhancement.	- Correct and complete evaluation reports.
11.Output (AUN-QA 11)	-The average time to graduate is established, monitored and benchmarked for improvement. -Employability of graduates is established, monitored and benchmarked for improvement. -The types and quantity of research activities by students are established, monitored and benchmarked for improvement. -The satisfaction levels of stakeholders are established, monitored and benchmarked for improvement.	-Complete evaluation reports

Table 3. Customers, with desirable qualities, and needs for information.

Customers	Desirable Qualities	Needs for Information
Graduated students	Having work performance skills.	- Information on the number of graduated students.

Table 4. Consumers, with activities and needs for information.

Consumers	Activities	Needs for Information
1. Entrepreneurs	Employing graduated students with desirable characteristics including good virtues and morality, good knowledge and intellectual skills, good human relationship skills, good responsibility, good numerical analysis skill, good communication skill, and good information technology usage skills, etc [2], [3], [4], [5] and [6].	- Questionnaires to assess the employer's satisfaction with the employed graduated student on various aspects of desirable characteristics.

Manufacturer: Manufacturer mean the university is regarded as a service provider university that produces graduated students. It performs the duty to transform raw materials, or entering students, into the finished products of qualified graduated students. The university will perform its duty of student Implementation and evaluation based upon quality assurance in education (AUNQA1 – AUNQA 11) of each activity, namely, expected learning outcomes, program structure and content, teaching and learning approach, student assessment, academic staff quality, support staff quality, student quality and support, facilities and infrastructure, quality enhancement and output. The final outcomes of the Manufacturer, ie. Graduates with desirable quality outcomes are delivered to the society.

Customers: Customers mean graduated student with desirable quality from the university.

Consumers: Graduate student identifies the society as the end customer or the consumer in this integrated supply chain. As universities are part of the society, the final outcomes of this supply chain, including graduates with desirable quality outcomes are delivered to the society as the end-of-process component of the supply chain information system model. They include the society in general and entrepreneurs who receive and/or employ the students who graduated from the university. Finally, the end product of qualified graduated students will provide added value to the supply chain [9], [10], [11], [12], [13] and [4].

The results of evaluation supply chain management information system model for quality assurance in educational management for AUN-QA is show in *Table 5* below:

Table 5. The assessment of the suitability supply chain management information system model for quality assurance in educational management for AUN-QA.

No.	Items	$\bar{X}$	S.D.	Suitability
1	Main components	3.56	0.51	High
2	Suppliers	3.60	0.61	High
3	Manufacturer	3.73	0.45	High
4	Customers	3.66	0.48	High
5	Consumers	3.60	0.50	High
	[illegible]	3.63	0.51	High

Referring to *Table 5*, it is found that the experts agree that supply chain management information system model for quality assurance in educational management for AUN-QA is highly appropriate, with the total rating mean 3.63 and standard deviation of 0.51.

6 | Conclusion and Discussion

Supply chain management information system model for quality assurance in educational management for AUN-QA have five components: Main components and Minor ingredients namely Suppliers, Manufacturer, Customers, Consumers after the experts have evaluated, it was found that supply chain management information system model for quality assurance in educational management for AUN-QA shows the overall rating mean of 3.63 and standard deviation of 0.51, which means Supply chain management information system model for quality assurance in educational management for AUN-QA is considered to be highly appropriate and the design is according to the review of documents and relevant literature from both within and outside the country with the research of Chansamut and Piriyasurawong has studied supply chain and information system about educational [2] and [6]. Moreover, with the study of Chansamut it reveals that supply chain and information technology as well [3], [4], [6] and [7].

7 | Suggestions

Further in-depth studies should be conducted on the creation of required database for the developed model.

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E-ISSN: 2717-2937 | P-ISSN: 2783-1337

International Journal of Research in Industrial Engineering

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Int. J. Res. Ind. Eng. Vol. 10, No. 4 (2021) 318–331.

Paper Type: Research Paper

Optimal Control Strategy on the Transmission Dynamics of Human Papillomavirus (HPV) and Human Immunodeficiency Viruses (HIV) Coinfection

Eshetu Dadi Gurmu[1,*], Boka Kumsa Bole[1], Purnachandar Rao Koya[1]

Department of Mathematics, Wollega University, Nekemte, Ethiopia; eshetudadi1@gmail.com; abitb2012@gmail.com; drkpraophd@gmail.com.

Citation:

Gurmu, E. D., Bole, B. K., & Koya, P. R. (2021). Optimal control strategy on the transmission dynamics of human papillomavirus (HPV) and human immunodeficiency viruses (HIV) coinfection. *International journal of research in industrial engineering, 10* (4), 318-331.

Received: 10/07/2021 Reviewed: 18/08/2021 Revised: 18/11/2021 Accepted: 20/11/2021

Abstract

In this paper, optimal control theory is applied to Human Papillomavirus (HPV) and Human immunodeficiency viruses (HIV) coinfection model given by using a system of ordinary differential equations. Optimal control strategy was employed to study the effect of combining various intervention strategies on the transmission dynamics of HPV-HIV coinfection diseases. The necessary conditions for the existence of the optimal controls were established using Pontryagin's Maximum Principle. Optimal control system was performed with help of Runge-Kutta forward-backward sweep numerical approximation method. Finally, numerical simulation illustrated that a combination of prevention, screening and treatment is the most effective strategy to minimize the disease from the community.

Keywords: Coinfection, Mathematical model, Stability, Optimal control, Simulation.

1 | Introduction

Human Papillomavirus infection is an infection caused by Human Papillomavirus (HPV), a DNA virus from the Papillomaviridae family [1]. According to the Centers for Disease Control and Prevention (CDC), HPV is the most common Sexually Transmitted Infection (STI) and about 90% eliminated on their own within two years [2]-[3]. In the worldwide, there are 18.1 million new cases, 9.6 million cancer related deaths, and 43.8 million people living with cancer in 2018. The number of new cases is expected to rise from 18 million to 22 million by 2030 and the number of global cancer deaths is projected to increase by 45% by 2030 [4], [5].

Human Immunodeficiency Viruses (HIV) are an RNA retrovirus. HIV translates its RNA to DNA with a viral enzyme called reverse transcriptase [6]. The target cell of HIV is CD4 T cells. A healthy human body has about 1000/mm3 of CD4 T cells. When the CD4 T cells of a patient decline to 200/mm3 or below, then that person is classified as having AIDS [7]. In the world, new HIV infections among young women aged 15–24 years were reduced by 25% between 2010 and 2018.

Corresponding Author: eshetudadi1@gmail.com

http://dx.doi.org/10.22105/riej.2021.294463.1234

The annual number of deaths from AIDS-related illness among people living with HIV globally has fallen from a peak of 1.7 million in 2004 to 770 000 in 2018. The global decline in deaths has largely been driven by progress in eastern and southern Africa, which is home to 54% of the world's people living with HIV. AIDS-related mortality in the region declined by 44% from 2010 to 2018. The annual number of new infections since 2010 has declined from 2.1 million to 1.7 million in 2018 [8].

Co-infection is more than one disease co-existing within a single host. HPV and HIV/AIDS are among the diseases that contaminate a large number of individuals worldwide. HPV-HIV is the co-infection of two diseases responsible for loss of many lives. People with a weakened immune system such as those with HIV/AIDS are susceptible to diseases such as HPV. The patient with the co-infection is observed to have some of the symptoms including dry cough, weakness and difficulty in breathing [9]. If the body immune system is strong, HPV infection can be fought off. For HIV/AIDS victims, the sexually transmitted diseases are the ones causing very serious sickness and if not treated they cause death as well [10]. When an individual is co-infected with HPV and HIV at acute and clinical latency stages is called the initial stage. The final stage of the co-infection of HIV and HPV involves AIDS and Cervical cancer.

The aim of this work is to study the effect of incorporating optimal control strategies to the mathematical model of HIV/AIDS and HPV co-infection in [11].

2 | Model Assumption

The total sexually active population at time t, denoted by $N(t)$ is sub-divided into thirteen mutually-exclusive compartments, namely susceptible individuals, which are capable of becoming infected $S(t)$, individuals who are exposed to HIV $E_h(t)$, individuals who are exposed to HPV $E_p(t)$, individuals who are exposed to both HIV and HPV $E_{hp}(t)$, asymptomatic to HIV but show no symptoms of the disease $A_h(t)$, asymptomatic to HPV but show no symptoms of the disease $A_p(t)$, asymptomatic to both HI-V and HPV but show no symptoms of the disease $A_{hp}(t)$, infected individuals with clinical symptoms of HIV $I_h(t)$, infected individuals with clinical symptoms of HPV $I_p(t)$, infected individuals with clinical symptoms of both HIV and HPV $I_{hp}(t)$, individuals having AIDS $A(t)$, individuals having Cervical cancer $C(t)$, individuals having both AIDS and Cervical cancer $AC(t)$ [11]. The total population at time t is given by

$$\begin{aligned} N(t) = S(t) + E_h(t) + E_p(t) + E_{hp}(t) + A_h(t) + A_p(t) + A_{hP}(t) + I_h(t) \\ + I_p(t) + I_{hp}(t) + A(t) + C(t) + AC(t). \end{aligned} \tag{1}$$

The susceptible population is increased by the recruitment of individuals (assumed susceptible) into the population at a rate Π. Susceptible individuals acquire HIV infection with infection force of $\lambda_h = \left[\beta_h q_h(\gamma_1 A_h + \gamma_2 I_h)\right]/[N]$. Here β_h is a transmission rate of HIV infection, q_h is a mean number of contacts and infectivity rates of HIV infection are γ_1 and γ_2 with $\gamma_2 > \gamma_1$. Similarly, susceptible individuals acquire HPV infection with infection force of $\lambda_p = \left[\beta_p q_p(\gamma_3 A_p + \gamma_4 I_p)\right]/[N]$. Here β_p is a transmission rate of HPV infection, q_p is a mean number of contacts and infectivity rates of HPV infection are γ_3 and γ_4 with $\gamma_4 > \gamma_3$. Finally susceptible individuals acquire both HIV and HPV infection with infection force of $\lambda_{hp} = \left[\beta_{hp} q_{hp}(\gamma_5 A_{hp} + \gamma_6 I_{hp})\right]/[N]$. Here β_{hp} is a transmission rate of HIV and HPV infection, q_{hp} is a mean number of contacts and infectivity rates of multiple infections are γ_5 and γ_6 with $\gamma_6 > \gamma_5$. Individuals in class E_h, E_p and E_{hp} progress to the symptomatic individuals I_h, I_p and I_{hp} with probability p, q and e respectively. Individuals in class E_h, E_p and E_{hp} progress to the asymptomatic individuals A_h, A_p and A_{hp} with probability $(1-p)$, $(1-q)$ and $(1-e)$ respectively. Individuals in E_h and E_p compartments move to E_{hp} with rate θ_1 and θ_2 respectively. Individuals in class A_h and A_p may asymptomatic to both infection A_{hp} with a rate θ_3 and θ_4 respectively. Individuals in class I_h and I_p may symptomatic to both infection I_{hp} with a rate θ_5 and θ_6 respectively. Individuals in class A_h, A_p and A_{hp} after having a symptom of HIV, HPV, and HIV-HPV move to class A, C and AC with rate ω_1, ω_2 and ω_3 respectively. Individuals in class I_h, I_p and I_{hp} compartments may develop AIDS, Cervical cancer and co-infection of AIDS and cervical cancer with the progression rates α_1, α_2 and α_3 respectively. Finally, individuals in A and C may develop co-infection of HIV-HPV (AC) with rates ε_1 and ε_2 respectively. All individuals have natural mortality rate μ [11].

Based on the model assumptions, the model equations are given as follows:

$$\begin{aligned}
&dS/dt = \Pi - (\lambda_h + \lambda_p + \lambda_{hp})S - \mu S,\\
&dE_p/dt = \lambda_p S - (\eta + \theta_2 + \mu)E_p,\\
&dE_h/dt = \lambda_h S - (\eta + \theta_1 + \mu)E_h,\\
&dE_{hp}/dt = \lambda_{hp} S + \theta_1 E_h + \theta_2 E_p - (\eta + \mu)E_{hp},\\
&dA_p/dt = (1-q)\eta E_p - (\omega_3 + \theta_4 + \mu)A_p,\\
&dA_h/dt = (1-p)\eta E_h - (\omega_1 + \theta_3 + \mu)A_h,\\
&dA_{hp}/dt = (1-e)\eta E_{hp} + \theta_3 A_h + \theta_4 A_p - (\omega_2 + \mu)A_{hp},\\
&dI_p/dt = q\eta E_p - (\alpha_3 + \theta_6 + \mu)I_p,\\
&dI_h/dt = p\eta E_h - (\alpha_1 + \theta_5 + \mu)I_h,\\
&dI_{hp}/dt = e\eta E_{hp} + \theta_5 I_h + \theta_6 I_p - (\alpha_2 + \mu)I_{hp},\\
&dC/dt = \alpha_3 I_p + \omega_3 A_p - (\varepsilon_2 + \mu)C,\\
&dA/dt = \alpha_1 I_h + \omega_1 A_h - (\varepsilon_1 + \mu)A,\\
&dAC/dt = \alpha_2 I_{hp} + \omega_2 A_{hp} + \varepsilon_1 A + \varepsilon_2 C - \mu AC,\\
&\text{Here, } \lambda_h = [\beta_h q_h(\gamma_1 A_h + \gamma_2 I_h)]/[N],\\
&\lambda_p = [\beta_p q_p(\gamma_3 A_p + \gamma_4 I_p)]/[N],\\
&\lambda_{hp} = [\beta_{hp} q_{hp}(\gamma_5 A_{hp} + \gamma_6 I_{hp})]/[N].
\end{aligned} \tag{2}$$

With initial condition

$$\begin{aligned}
&S(0) > S_0, \quad E_h(0) \geq E_{h0}, \quad E_p(0) \geq E_{p0},\\
&E_{hp}(0) \geq E_{hp0}, \quad A_h(0) \geq A_{h0}, \quad A_p(0) \geq A_{p0}, \quad A_{hp}(0) \geq A_{hp0}, \quad I_h(0) \geq I_{h0}, \quad I_p(0) \geq I_{p0}, \quad I_{hp}(0) \geq I_{hp0}, \quad A(0) \geq A_0,\\
&C(0) \geq C_0, \quad AC(0) \geq AC_0.
\end{aligned} \tag{3}$$

3 | Optimal Control Analysis of the Model

In this section, we introduce optimal control strategies to the HPV-HIV coinfection model in [11]. The model *Eq. (2)* is modified by introducing control function; $u_1(t)$ represents HPV prevention effort, $u_2(t)$

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represents HIV prevention effort, $u_3(t)$ represents HPV screening effort, $u_4(t)$ represents HIV screening effort, $u_5(t)$ represents HPV infection treating effort and $u_6(t)$ represents HIV infection treating effort. Time is specified and is relatively short and is given by $t \in [0, T]$, T is the terminal time. Thus, the corresponding state system for the model *Eq. (1)* is given as follows:

$$
\begin{aligned}
dS/dt &= \Pi - \left((1-u_1)\lambda_p + (1-u_2)\lambda_h + (1-u_1)(1-u_2)\lambda_{hp} + \mu\right)S,\\
dE_p/dt &= (1-u_1)\lambda_p S - (1-u_3)\eta E_p - (\theta_2+\mu)E_p,\\
dE_h/dt &= (1-u_2)\lambda_h S - (1-u_4)\eta E_h - (\theta_1+\mu)E_h,\\
dE_{hp}/dt &= (1-u_1)(1-u_2)\lambda_{hp} S + \theta_1 E_h + \theta_2 E_p - (1-u_1)(1-u_2)\eta E_{hp} - \mu E_{hp},\\
dA_p/dt &= (1-u_3)(1-q)\eta E_p - (u_5+\omega_3+\theta_4+\mu)A_p,\\
dA_h/dt &= (1-u_4)(1-p)\eta E_h - (u_6+\omega_1+\theta_3+\mu)A_h,\\
dA_{hp}/dt &= (1-u_3)(1-u_4)(1-e)\eta E_{hp} + \theta_3 A_h + \theta_4 A_p - (u_5+u_6+\omega_2+\mu)A_{hp}, \qquad (4)\\
dI_p/dt &= (1-u_3)q\eta E_p - (u_5+\alpha_3+\theta_6+\mu)I_p,\\
dI_h/dt &= (1-u_4)p\eta E_h - (u_6+\alpha_1+\theta_5+\mu)I_h,\\
dI_{hp}/dt &= (1-u_3)(1-u_4)e\eta E_{hp} + \theta_5 I_h + \theta_6 I_p - (u_5+u_6+\alpha_2+\mu)I_{hp},\\
dC/dt &= (u_5+\alpha_3)I_p + (u_5+\omega_3)A_p - (\varepsilon_2+\mu)C,\\
dA/dt &= (u_6+\alpha_1)I_h + (u_6+\omega_1)A_h - (\varepsilon_1+\mu)A,\\
dAC/dt &= (u_5+u_6+\alpha_2)I_{hp} + (u_5+u_6+\omega_2)A_{hp} + \varepsilon_1 A + \varepsilon_2 C - \mu AC.
\end{aligned}
$$

The main objective is to determine the optimal control values $u^* = (u_1^*, u_2^*, u_3^*, u_4^*, u_5^*, u_6^*)$ of the controls $u = (u_1, u_2, u_3, u_4, u_5, u_6)$ such that the associated state trajectories $\overline{S}$, $\overline{E_p}$, $\overline{E_h}$, $\overline{E_{ph}}$, $\overline{A_h}$, $\overline{A_p}$, $\overline{A_{ph}}$, $\overline{I_h}$, $\overline{I_p}$, $\overline{I_{ph}}$, $\overline{C}$, $\overline{A}$, $\overline{CA}$ are solution of the system *Eq. (4)* in the intervention time interval [0, T] with initial condition in *Eq. (3)* and minimize the objective functional. The controls are bounded between 0 and 1. When the controls vanish, it means no extra measures are implemented for the reduction of the disease. When the controls take the maximum value 1, it means that the intervention is 100% perfectly implemented which is not time in reality and thus we assumed $u_i \leq 1 - \epsilon$, $i = 1,2,3,4,5,6$, where $\epsilon \ll 1$ denotes a positive real number. Our cost functional considers the number of exposed individuals E_h, E_p, E_{ph}, the number of asymptomatic individuals A_h, A_p, A_{ph}, the number of symptomatic individuals I_h, I_p, I_{ph} and the implementation cost of strategies related to the controls $u_i, i = 1,2,3,4,5,6$. Thus, the objective functional is given by

$$
\begin{aligned}
J(u) = \int_0^T [&M_1E_p(t) + M_2E_h(t) + M_3E_{ph}(t) + M_4A_p(t) + M_5A_h(t) + M_6A_{ph}(t) + \\
&M_7I_p(t) + M_8I_h(t) + M_9I_{ph}(t) + \tfrac{1}{2}\textstyle\sum_{i=1}^{6} B_i u_i^2]dt \rightarrow \min.
\end{aligned} \qquad (5)
$$

Where constants M_i and B_i are positive. The weight constants B_1, B_2, B_3, B_4, B_5 and B_6 are the measure of relative costs of interventions associated with the controls u_1, u_2, u_3, u_4, u_5 and u_6, respectively, and also balances the units of integrand. Additionally, the functional J corresponds the total cost due to cervical cancer and AIDS outbreak and its control strategies. Further, the integrand function

$$L(\varnothing, u) = M_1E_p(t) + M_2E_h(t) + M_3E_{ph}(t) + M_4A_p(t) + M_5A_h(t) + M_6A_{ph}(t) + M_7I_p(t) + M_8I_h(t) + M_9I_{ph}(t) + \frac{1}{2}\sum_{i=1}^{6} B_iu_i^2,$$

measures the current cost at time t. Finally, the fixed constant T denotes the terminal innervations time. The set of admissible control functions is defined by

$$\Omega = \left\{\left(u_1(.), u_2(.), u_3(.), u_4(.), u_5(.), u_6(.)\right) \in \left(L^\infty(0,T)\right)^6 : 0 \le u_i(t) \le 1 - \epsilon, \forall_t \in [0,T]\right\}. \quad (6)$$

Then we consider the optimal control problem of obtaining $(\bar{S}(.), \overline{E_p}(.), \overline{E_h}(.), \overline{E_{ph}}(.), \overline{A_h}(.), \overline{A_p}(.), \overline{A_{ph}}(.), \overline{I_h}(.), \overline{I_p}(.), \overline{I_{ph}}(.), \bar{C}(.), \bar{A}(.), \overline{CA}(.))$ associated with admissible controls $\left(u_1(.), u_2(.), u_3(.), u_4(.), u_5(.), u_6(.)\right) \in \Omega$ on the intervention time interval $[0,T]$, subject to the state system *Eq. (4)* in $\mathbb{R}^{13}$ with initial condition given in *Eq. (3)* and minimizing the cost functional *Eq. (5)*. Thus, the optimal control problem can be defined as

$$J(u_1^*, \quad u_2^*, \; u_3^*, \quad u_4^*, u_5^*, u_6^*) = \min_{\Omega} J\left(u_1(.), u_2(.), u_3(.), u_4(.), u_5(.), u_6(.)\right). \quad (7)$$

Satisfying *Eq. (4)* and *Eq. (3)*.

3.1 | Existence of Optimal Controls

In this subsection, we prove the existence of such optimal control functions which minimize the cost function in the finite intervention period. The following result guarantees the existence of optimal control functions. A detail and similar analysis on existence of optimal control can be obtained in [12]-[13].

Theorem 1. There exists an optimal control $u^* = (u_1^*, \; u_2^*, \; u_3^*, \; u_4^*, \; u_5^*, u_6^*)$ in Ω and a corresponding solution vector $\bar{X} = (\bar{S}, \; \overline{E_p}, \; \overline{E_h}, \overline{E_{ph}}, \overline{A_h}, \overline{A_p}, \; \overline{A_{ph}}, \; \overline{I_h}, \; \overline{I_p}, \; \overline{I_{ph}}, \bar{C}, \; \bar{A}, \overline{CA})$ to the initial value problem *Eq. (3)* and *Eq. (4)* such that

$$J(u_1^*, \quad u_2^*, \; u_3^*, \quad u_4^*, u_5^*, u_6^*) = \min_{\Omega} J\left(u_1(.), u_2(.), u_3(.), u_4(.), u_5(.), u_6(.)\right).$$

Proof. The entire state variables involved in the model are continuously differentiable. Therefore, we need to verify the following four conditions as given in [12]

I. The set of solutions to the system *Eq. (4)* with control variables are non empty.
II. The set Ω is convex and closed.
III. The state system can be written as linear function of control variables with coefficients depending on time and state variables.
IV. The integrand L of *Eq. (5)* is convex on Ω and $L(\varnothing, u) \ge g(u)$, where g continuous and $\|u\|^{-1}g(u) \to +\infty$ as $\|u\| \to \infty$.

Since the total population in *Eq. (2)* is defined as

$$N(t) = S(t) + E_h(t) + E_p(t) + E_{hp}(t) + A_h(t) + A_p(t) + A_{hP}(t) + I_h(t) + I_p(t) + I_{hp}(t) + A(t) + C(t) + AC(t).$$

From governing system *Eq. (4)* it follows that

$$dN/dt = \Pi - \mu N.$$

It follows that the solutions of the state system are continuous and bounded for each admissible control functions in Ω. Further, the right-hand side functions of the model *Eq. (4)* satisfy the Lipschitz condition

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with respect to state variables. Therefore, the initial value problem *Eq. (4)* and *Eq. (3)* has a unique solution corresponding to each admissible control function $u \in \Omega$. Thus, *Condition (1)* is proved.

To prove *Condition (2)*, consider

$$\Omega = \{u \in \mathbb{R}^6: ||u|| \leq 1 - \epsilon\}.$$

Let $u_1, u_2 \in \Omega$ such that $\|u_1\| \leq 1 - \epsilon$ and $\|u_2\| \leq 1 - \epsilon$. Then for any $\lambda \in [0,1]$,

$$||\lambda u_1 + (1-\lambda)u_2|| \leq \lambda||u_1|| + (1-\lambda)||u_2|| \leq 1 - \epsilon.$$

This implies that Ω is convex and closed. The state system *Eq. (4)* is linear in control variables u_1, u_2, u_3, u_4, u_5 and u_6 with coefficients depending on state variables. With this *Condition (3)* is satisfied. The integrand of the cost functional is the sum of convex function and hence convex with respect to control variables. Furthermore,

$$L(\emptyset, u) = M_1E_p(t) + M_2E_h(t) + M_3E_{ph}(t) + M_4A_p(t) + M_5A_h(t) + M_6A_{ph}(t) + M_7I_p(t) + M_8I_h(t) + M_9I_{ph}(t) + \frac{1}{2}\sum_{i=1}^{6} B_iu_i^2 \geq \frac{1}{2}\sum_{i=1}^{6} B_iu_i^2. \tag{8}$$

Let $\chi = min\left(\frac{1}{2}\sum_{i=1}^{6} B_iu_i^2\right) > 0$ and define a continuous function $g(u) = \chi\|u\|^{-1}$. Then from *Eq. (8)* we have $L(\emptyset, u) \geq g(u)$. Clearly, $\|u\|^{-1}g(u) \to +\infty$ as $\|u\| \to \infty$. Thus, condition (4) is achieved. Therefore, the existence of an optimal control pair $(\overline{X}, u^*)$ is satisfying *Eq. (4)* and *Eq. (7)* is assured by results given in [12]. Hence the proof.

3.2 | Characterization of Optimal Control

In this section, we determine optimality conditions for the optimal control problem defined above and its detail properties. According to Pontryagin's Maximum Principle [14] if $u^*(.) \in \Omega$ is optimal for problem *Eq. (4)* and *Eq. (7)* with fixed final time T, then there exists a non trivial absolutely continuous mapping $\lambda: [0, T] \to \mathbb{R}^{13}$, $\lambda = (\lambda_1(t), \lambda_2(t), \lambda_3(t), \lambda_4(t), \lambda_5(t), \lambda_6(t), \lambda_7(t), \lambda_8(t), \lambda_9(t), \lambda_{10}(t), \lambda_{11}(t), \lambda_{12}(t), \lambda_{13}(t))$ called the adjoint vector, such that

I. The Hamiltonian function is defined as

$$H = M_1E_p(t) + M_2E_h(t) + M_3E_{ph}(t) + M_4A_p(t) + M_5A_h(t) + M_6A_{ph}(t) + M_7I_p(t) + M_8I_h(t) + M_9I_{ph}(t) + \frac{1}{2}\sum_{i=1}^{6} B_iu_i^2 + \sum_{i=1}^{13} \lambda_i(t)g_i(t, \emptyset, u). \tag{9}$$

Where g_i stands for the right hands of the *Constraints (4)* for $i = 1, \ldots, 13$.

II. The control system

$$S' = \frac{\partial H}{\partial \lambda_1}, E_p' = \frac{\partial H}{\partial \lambda_2}, E_h' = \frac{\partial H}{\partial \lambda_3}, E_{ph}' = \frac{\partial H}{\partial \lambda_4}, A'_p = \frac{\partial H}{\partial \lambda_5}, A'_h = \frac{\partial H}{\partial \lambda_6}, A'_{ph} = \frac{\partial H}{\partial \lambda_7}, I_p' = \frac{\partial H}{\partial \lambda_8}, I_h' = \frac{\partial H}{\partial \lambda_9}, I_{ph}' = \frac{\partial H}{\partial \lambda_{10}}, C = \frac{\partial H}{\partial \lambda_{11}}, A = \frac{\partial H}{\partial \lambda_{12}}, CA = \frac{\partial H}{\partial \lambda_{13}}. \tag{10}$$

III. The adjoint system

$$\lambda_1' = -\frac{\partial H}{\partial S}, \lambda_2' = -\frac{\partial H}{\partial E_p}, \lambda_3' = -\frac{\partial H}{\partial E_h}, \lambda_4' = -\frac{\partial H}{\partial E_{ph}}, \lambda_5' = -\frac{\partial H}{\partial A_p}, \lambda_6' = -\frac{\partial H}{\partial A_h}, \lambda_7' = -\frac{\partial H}{\partial A_{ph}}, \lambda_8' = -\frac{\partial H}{\partial I_p}, \lambda_9' = -\frac{\partial H}{\partial I_h}, \lambda_{10}' = -\frac{\partial H}{\partial I_{ph}}, \lambda_{11}' = -\frac{\partial H}{\partial C}, \lambda_{12}' = -\frac{\partial H}{\partial A}, \lambda_{13}' = -\frac{\partial H}{\partial CA}. \tag{11}$$

IV. The optimality conditions

$$H\left(\emptyset^*(t), u^*(t), \lambda^*(t)\right) = \min_{u \in \Omega} H\left(\emptyset^*(t), u^*(t), \lambda^*(t)\right). \tag{12}$$

V. Moreover, the transversality condition

$$\lambda_i(T) = 0, \quad i = 1, \dots, 13. \tag{13}$$

holds for almost all $t \in [0, T]$.

In the next result, we discuss characterization of optimal controls and adjoint variables.

Theorem 2. Let $u^* = (u_1^*,\ u_2^*,\ u_3^*,\ u_4^*, u_5^*,\ u_6^*)$ be the optimal control and $(\overline{S}(.),\ \overline{E_p}(.),\ \overline{E_h}(.), \overline{E_{ph}}(.), \overline{A_h}(.), \overline{A_p}(.),\ \overline{A_{ph}}(.),\ \overline{I_h}(.),\ \overline{I_p}(.),\ \overline{I_{ph}}(.), \overline{C}(.),\ \overline{A}(.), \overline{CA}(.))$ be associated unique optimal solutions of the optimal control problem *Eq. (4)* and *Eqs. (6)-(7)* with fixed final time T. Then there exists adjoint function $\lambda_i^*(.),\ \ i = 1, \dots, 13$ satisfying the following canonical equations

$$\frac{d\lambda_1}{dt} = \lambda_1[(1-u_1)\lambda_p + (1-u_2)\lambda_h + (1-u_1)(1-u_2)\lambda_{ph} + \mu] - \lambda_2(1-u_1)\lambda_p - \lambda_3(1-u_2)\lambda_h - \lambda_4(1-u_1)(1-u_2)\lambda_{ph}],$$

$$\frac{d\lambda_2}{dt} = -M_1 + \lambda_2[(1-u_3)\eta + (\theta_2+\mu)] - \lambda_4\theta_2 - \lambda_5(1-u_3)(1-q)\eta - \lambda_8(1-u_3)q\eta, \tag{14}$$

$$\frac{d\lambda_3}{dt} = -M_2 + \lambda_3[(1-u_4)\eta + (\theta_1+\mu)] - \lambda_4\theta_1 - \lambda_6(1-u_4)(1-p)\eta - \lambda_9(1-u_4)p\eta,$$

$$\frac{d\lambda_3}{dt} = -M_2 + \lambda_3[(1-u_4)\eta + (\theta_1+\mu)] - \lambda_4\theta_1 - \lambda_6(1-u_4)(1-p)\eta - \lambda_9(1-u_4)p\eta,$$

$$\frac{d\lambda_4}{dt} = -M_3 + \lambda_4[(1-u_3)(1-u_4)\eta + \mu] - \lambda_7(1-u_3)(1-u_4)(1-e)\eta - \lambda_{10}(1-u_3)(1-u_4)e\eta,$$

$$\frac{d\lambda_5}{dt} = -M_4 + \lambda_1\left[(1-u_1)\frac{\beta_p q_p \gamma_3 S}{N}\right] - \lambda_2\left[(1-u_1)\frac{\beta_p q_p \gamma_3 S}{N}\right] + \lambda_5(u_5 + \omega_3 + \theta_4 + \mu) - \lambda_7\theta_4 - \lambda_{11}(u_5 + \omega_3),$$

$$\frac{d\lambda_6}{dt} = -M_5 + \lambda_1\left[(1-u_2)\frac{\beta_h q_h \gamma_1 S}{N}\right] - \lambda_3\left[(1-u_2)\frac{\beta_h q_h \gamma_1 S}{N}\right] + \lambda_6(u_6 + \omega_1 + \theta_3 + \mu) - \lambda_7\theta_3 - \lambda_{12}(u_6 + \omega_1),$$

$$\frac{d\lambda_7}{dt} = -M_6 + \lambda_1\left[(1-u_1)(1-u_2)\frac{\beta_{ph} q_{ph} \gamma_5 S}{N}\right] - \lambda_4\left[(1-u_1)(1-u_2)\frac{\beta_{ph} q_{ph} \gamma_5 S}{N}\right] + \lambda_7(u_5 + +u_6 + \omega_2 + \mu) - \lambda_{13}(u_5 + u_6 + \omega_2),$$

$$\frac{d\lambda_8}{dt} = -M_7 + \lambda_1\left[(1-u_1)\frac{\beta_p q_p \gamma_4 S}{N}\right] - \lambda_2\left[(1-u_1)\frac{\beta_p q_p \gamma_4 S}{N}\right] + \lambda_8(u_5 + \alpha_3 + \theta_6 + \mu) - \lambda_{10}\theta_6 - \lambda_{11}(u_5 + \alpha_3),$$

$$\frac{d\lambda_9}{dt} = -M_8 + \lambda_1\left[(1-u_2)\frac{\beta_h q_h \gamma_2 S}{N}\right] - \lambda_3\left[(1-u_2)\frac{\beta_h q_h \gamma_2 S}{N}\right] + \lambda_9(u_6 + \alpha_1 + \theta_5 + \mu) - \lambda_{10}\theta_5 - \lambda_{12}(u_6 + \alpha_1),$$

$$\frac{d\lambda_{10}}{dt} = -M_9 + \lambda_1\left[(1-u_1)(1-u_2)\frac{\beta_{ph} q_{ph} \gamma_6 S}{N}\right] - \lambda_4\left[(1-u_1)(1-u_2)\frac{\beta_{ph} q_{ph} \gamma_6 S}{N}\right] + \lambda_{10}(u_5 + u_6 + \alpha_2 + \mu) - \lambda_{13}(u_5 + u_6 + \alpha_2),$$

$$\frac{d\lambda_{11}}{dt} = \lambda_{11}(\xi_2 + \mu) - \lambda_{13}\xi_2,$$

$$\frac{d\lambda_{12}}{dt} = \lambda_{12}(\xi_1 + \mu) - \lambda_{13}\xi_1, \frac{d\lambda_{13}}{dt} = \lambda_{13}\mu.$$

With transiversality conditions

$$\lambda_i^*(T) = 0, \quad i = 1, \dots, 13. \tag{15}$$

Moreover, the corresponding optimal controls u_1^*, u_2^*, u_3^*, u_4^*, u_5^* and u_6^* are given by

$$\begin{aligned} u_1^*(t) &= \min\{\max\{0, \Phi_1\}, 1-\epsilon\}, \quad u_4^*(t) = \min\{\max\{0, \Phi_4\}, 1-\epsilon\}, \\ u_2^*(t) &= \min\{\max\{0, \Phi_2\}, 1-\epsilon\}, \quad u_5^*(t) = \min\{\max\{0, \Phi_5\}, 1-\epsilon\}, \\ u_3^*(t) &= \min\{\max\{0, \Phi_3\}, 1-\epsilon\}, \quad u_6^*(t) = \min\{\max\{0, \Phi_6\}, 1-\epsilon\}. \end{aligned} \tag{16}$$

Where

$$\Phi_1 = \frac{\lambda_p S(\lambda_2 - \lambda_1) + (1-u_2)\lambda_{ph} S(\lambda_4 - \lambda_1)}{B_1},$$

$$\Phi_2 = \frac{\lambda_h S(\lambda_3 - \lambda_1) + (1-u_1)\lambda_{ph} S(\lambda_4 - \lambda_1)}{B_2},$$

$$\Phi_3 = \frac{\lambda_5(1-q)\eta E_p + \lambda_7(1-u_4)(1-e)\eta E_{ph} + \lambda_8 q\eta E_p + \lambda_{10}(1-u_4)e\eta E_{ph} - \lambda_4(1-u_4)\eta E_{ph} - \lambda_2\eta E_p}{B_3},$$

$$\Phi_4 = \frac{\lambda_6(1-p)\eta E_h + \lambda_7(1-u_3)(1-e)\eta E_{ph} + \lambda_9 p\eta E_h + \lambda_{10}(1-u_3)e\eta E_{ph} - \lambda_4(1-u_3)\eta E_{ph} - \lambda_3\eta E_h}{B_4},$$

$$\Phi_5 = \frac{\lambda_5 A_p + \lambda_7 A_{ph} + \lambda_8 I_p + \lambda_{10} I_{ph} - \lambda_{11}(A_p + I_p) - \lambda_{13}(A_{ph} + I_{ph})}{B_5},$$

$$\Phi_6 = \frac{\lambda_6 A_h + \lambda_7 A_{ph} + \lambda_9 I_h + \lambda_{10} I_{ph} - \lambda_{12}(A_h + I_h) - \lambda_{13}(A_{ph} + I_{ph})}{B_6}.$$

Proof: The adjoint system, transversality conditions and optimality conditions are standard results from Pontryagin's Maximum Principle [12], [15]. Thus, system *Eq. (14)* is directly derived from *Eq. (11)* and the transversality conditions *Eq. (15)* follow from *Eq. (12)*. Further, using the optimality condition it follows that

$$\frac{\partial H}{\partial u_i} = 0, \text{ for } \quad i = 1, 2, 3, 4, 5, 6. \tag{17}$$

Consequently, the optimality controls *Eq. (16)* can be directly solved from *Eq. (17)* by taking into account the boundedness condition given in *Eq. (6)*.

3.3 | Uniqueness of the Optimality System

In order to successively discuss uniqueness of the optimality system we notice that the adjoint system is also linear in λ_i for $i = 1,2,3,4,5,6, \dots, 13$ with bounded coefficients. Thus, there exists a $M > 0$ such that $|\lambda_i(t)| < M$ for $i = 1,2,3,4,5,6, \dots, 13$ on $[0, T]$.

Theorem 3. For T sufficiently small the solution to the optimality system is unique [16].

4 | Numerical Simulation

In this section, we discuss the numerical simulation of the optimality system. Using the initial conditions $S(0) = 2500$, $E_h(0) = 700$, $E_p(0) = 600$, $E_{hp}(0) = 500$, $A_h(0) = 800$, $A_p(0) = 750$, $A_{hp}(0) = 700$, $I_h(0) = 500$, $I_p(0) = 400$, $I_{hp}(0) = 200$, $A(0) = 600$, $C(0) = 500$, $AC(0) = 400$ and also coefficients of the state and controls that we used are $M1 = 80, M2 = 75, M3 = 50, M4 = 80, M5 = 75, M6 = 50, M7 = 80, M8 = 75, M9 = 50, B1 = 100$, $B2 = 110, B3 = 120, B4 = 130, B5 = 125, B6 = 135$ a simulation study is conducted. Finally, an optimal control strategy is designed and discussed using different control strategies. To solve the optimal controls and states, we use the Runge-Kutta numerical method using MATLAB program. It needs to solve thirteen-state equations and thirteen adjoint equations. For that, first we solve system 2 with a guess for the controls forward in time and then using the transversality conditions as initial values and the adjoint system is solved backward in time using the current iteration solution of the state system.

Table 1. Parameter values used in simulations.

Parameter	Value	Source
Π	0.004	[1]
λ_h	0.00197	assumed
λ_p	0.002	assumed
λ_{hp}	0.0018	assumed
μ	0.02	[11]
α_1	0.016	[11]
α_2	0.017	[11]
α_3	0.011	[11]
p	0.067	[11]
q	0.067	[11]
e	0.067	[11]
θ_1	0.003	[11]
θ_2	0.003	[11]
θ_3	0.003	[11]
θ_4	0.003	[11]
θ_5	0.003	[11]
θ_6	0.003	[11]
ω_1	0.054	[11]
ω_2	0.064	[11]
ω_3	0.039	[11]
ε_1	0.001	[11]
ε_2	0.001	[11]
η	0.0024	[11]

Intervention I. Optimal use of u_2, u_3, u_4, u_5 and u_6: This intervention strategy combines prevention effort for HIV u_2 ,screening effort $(u_3\&u_4)$ and treatment effort $(u_5\&u_6)$ are used to optimize objective functional while setting prevention effort for HPV u_1 equal to zero. As shown in *Fig. 1*, the magnitudes of exposed and infectious population reduce more when controls are in use than the case without controls.

Intervention II. Optimal use of u_1, u_3, u_4, u_5 and u_6: This intervention combines prevention effort for HPV u_1, screening effort $(u_3\&u_4)$ and treatment effort $(u_5\&u_6)$ are used to optimize objective functional while setting prevention effort for HIV u_2 equal to zero. Results illustrate that the size of exposed and infectious population reduce sharply with controls more than the case without controls as shown in *Fig. 2*.

Intervention III. Optimal use of u_1, u_2, u_3, u_4 and u_5: This strategy illustrates effect of prevention effort ($u_1\& u_2$), screening effort $(u_3\&u_4)$ and treatment effort for HPV u_5 are used to optimize objective functional while setting treatment effort for HIV u_6 equal to zero. As expected, the number of exposed and infectious population diminishes more rapidly with controls than the case without controls as illustrated in *Fig. 3*.

Intervention IV. Optimal use of all controls u_1, u_2, u_3, u_4, u_5 and u_6: This intervention strategy uses prevention effort $(u_1\& u_2)$, screening effort $(u_3\&u_4)$ and treatment effort ($u_5\&u_6$) are used to optimize objective functional. The size of exposed and infectious population decreases more sharply when controls are in use than the case when controls are not used as described in *Fig. 4*.

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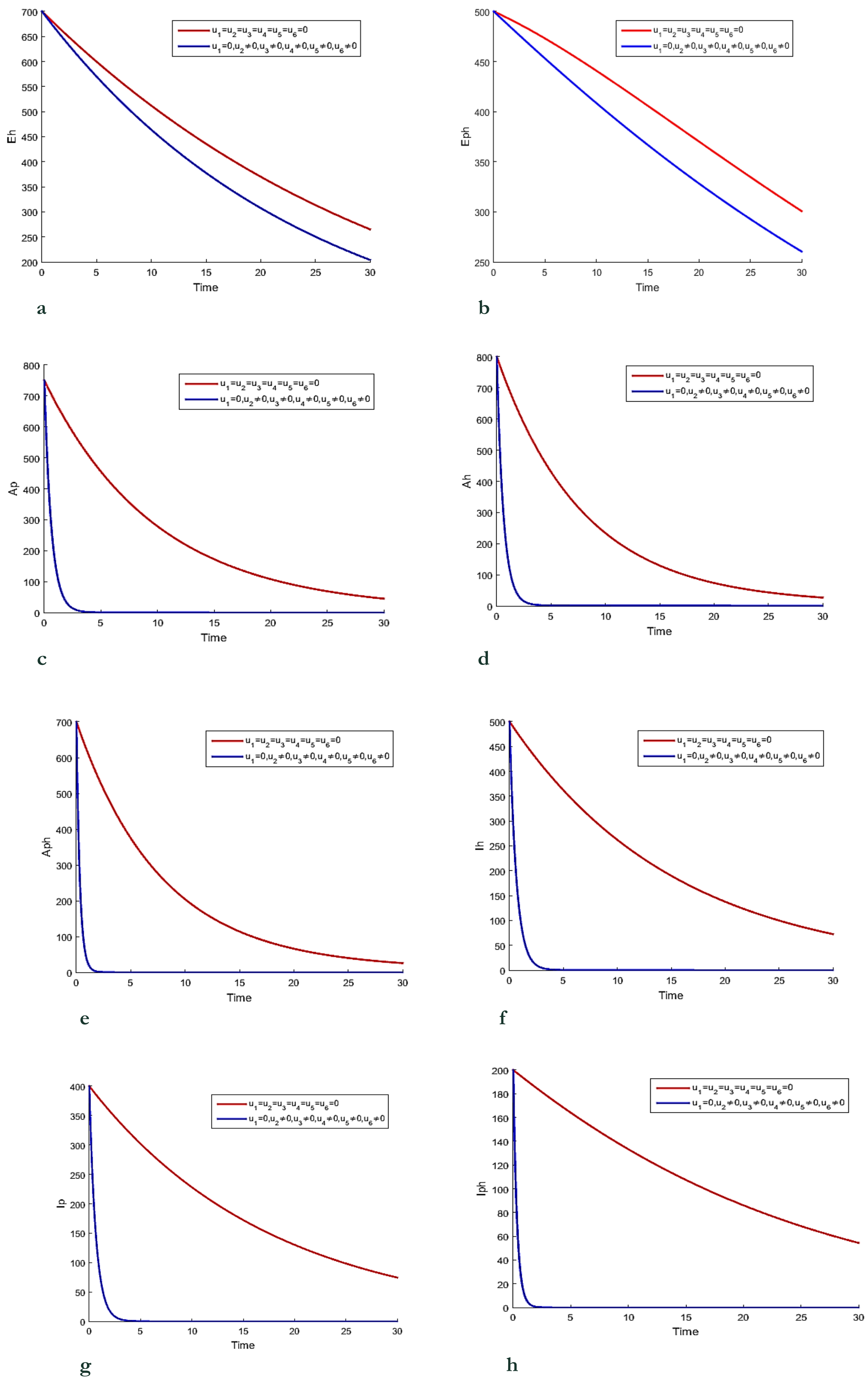

Fig 1. Simulations showing optimal use of u_2, u_3, u_4, u_5 and u_6.

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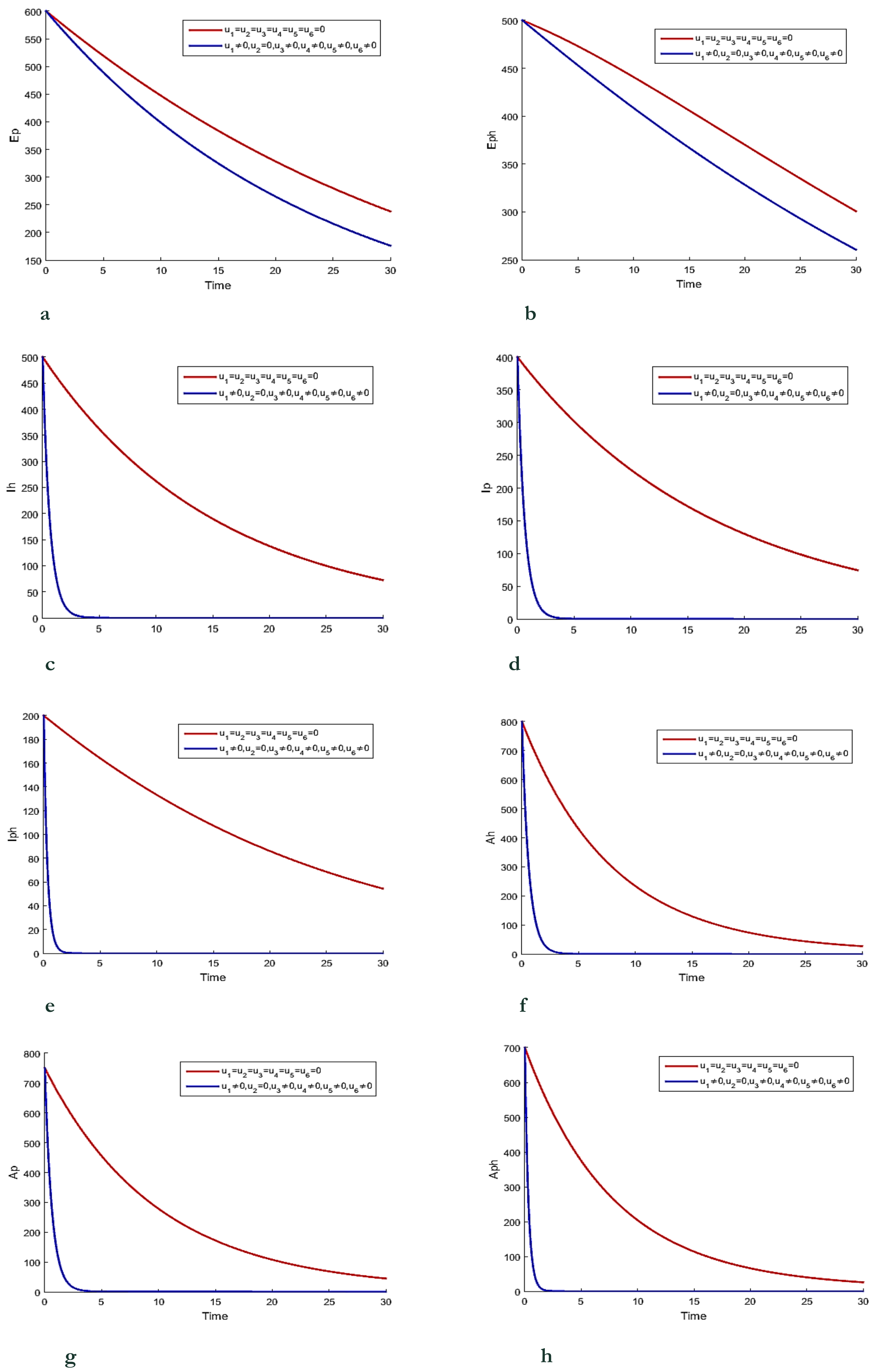

Fig. 2. Simulations showing optimal use of u_1, u_3, u_4, u_5 and u_6.

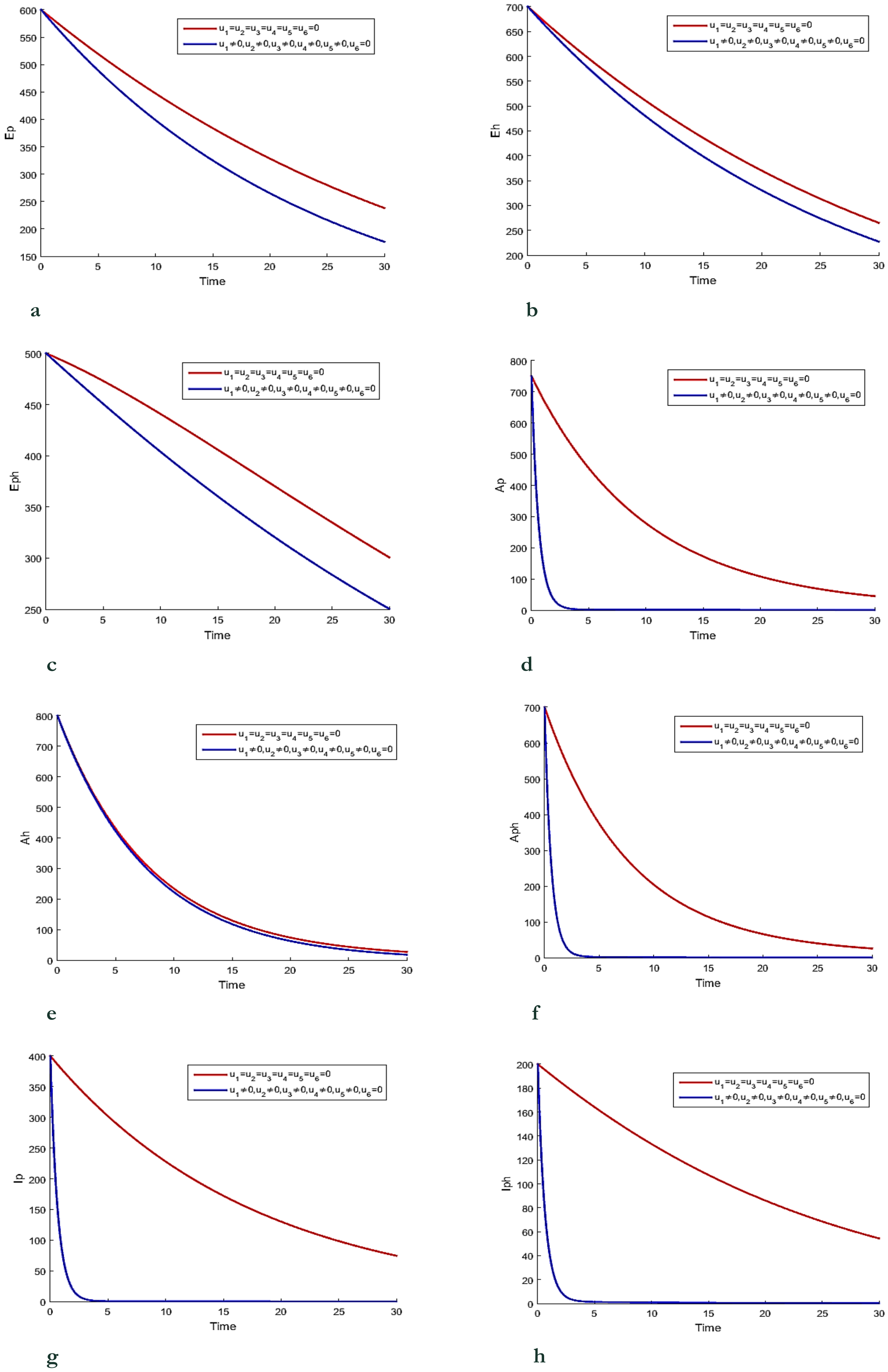

Fig 3. Simulations showing optimal use of u_1, u_2, u_3, u_4 and u_5.

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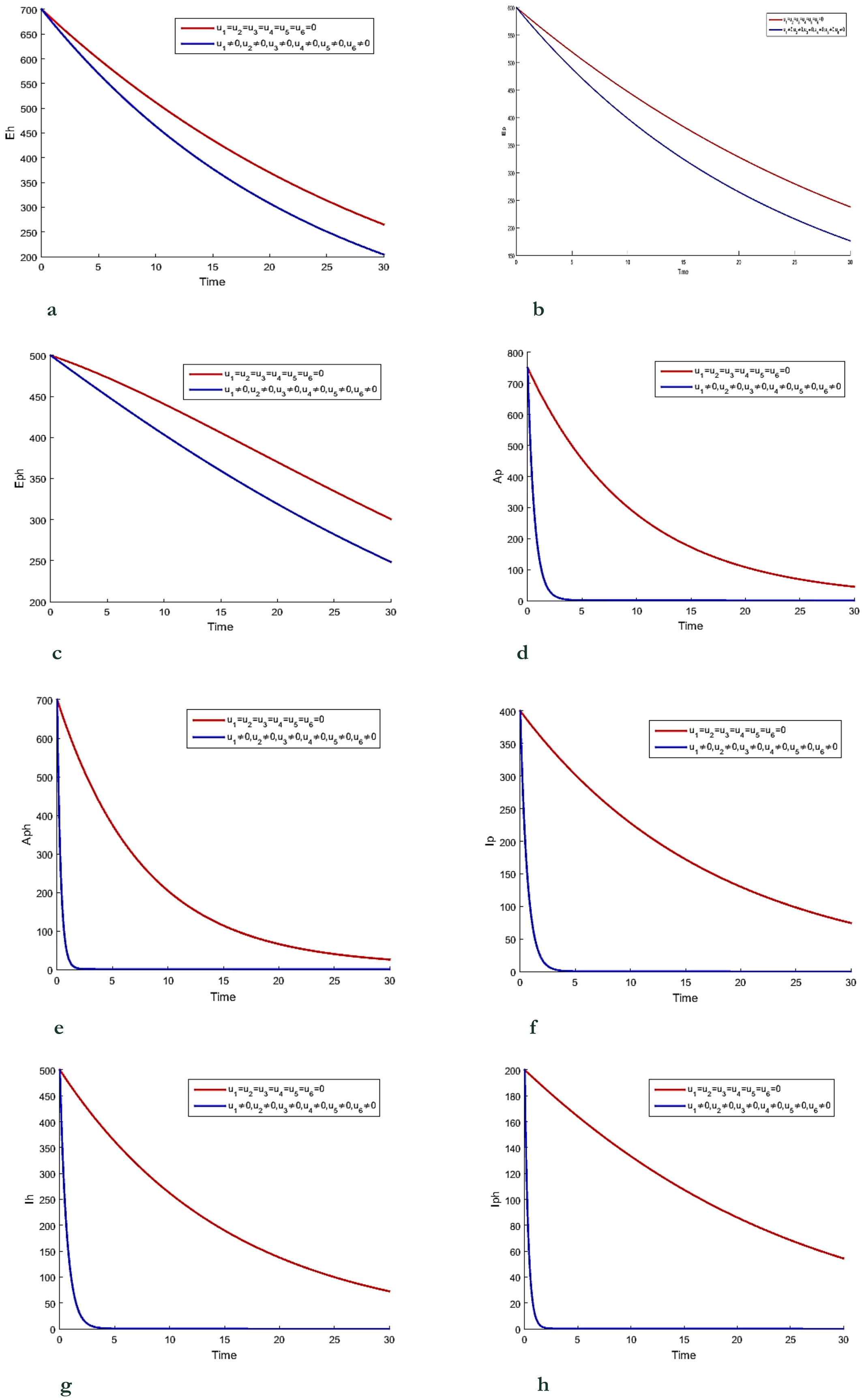

Fig 4. Simulations showing optimal use of u_1, u_2, u_3, u_4, u_5 and u_6.

5 | Conclusion

In this paper, an optimal control problem was formulated and analysed to study the effects of combining at least five control strategies on the transmission dynamics of HPV-HIV coinfection [11]. In this study, we have designed an optimal control problem that minimizes the cost for implementation of the controls while also minimizing the total exposed and infectious individuals over the intervention interval. The existence of optimal controls and characterization was established using Pontryagin's Maximum Principle. The results reveal that the size of exposed and infectious population is eradicated from the population by combining different intervention rather than using one intervention strategy.

HPV-HIV coinfection remain a challenge especially in developing countries, but from results of this study we recommend that, the government should introduce education programmers on the importance of voluntary and routinely screening on HPV-HIV coinfection. In future work, we plan to extend the study by incorporating protected and treatment class to HPV- HIV transmission dynamics.

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E-ISSN: 2717-2937 | P-ISSN: 2783-1337

International Journal of Research in Industrial Engineering

IJRIE

www.riejournal.com

Int. J. Res. Ind. Eng. Vol. 10, No. 4 (2021) 332–345.

Paper Type: Research Paper

Improving the Performance of Planning and Controlling Raw Material Inventory in Food Industry

Filscha Nurprihatin[1,*], Metta Gotami[2], Glisina Dwinoor Rembulan[2]

[1] Department of Industrial Engineering, Sampoerna University, Jakarta 12780, Indonesia; filscha.nurprihatin@sampoernauniversity.ac.id.
[2] Department of Industrial Engineering, University Bunda Mulia, Jakarta 14430, Indonesia; gotamimetta@gmail.com; grembulan@bundamulia.ac.id.

Citation:

Nurprihatin, F., Gotami, M., & Rembulan, G. D. (2021). Improving the performance of planning and controlling raw material inventory in food industry. *International journal of research in industrial engineering, 10* (4), 332-345.

Received: 27/09/2021 Reviewed: 12/03/2021 Revised: 16/11/2021 Accepted: 20/11/2021

Abstract

This paper discusses the inefficient and inaccurate raw material supply at a food company which results in a backlog. This means the overstock occurs so that the improvement of inventory control needs to be done. ABC classification is firstly utilized as input for Material Requirements Planning (MRP). This paper focuses on four products which are classified into A class. Then, this paper discusses the Triple Exponential Smoothing (TES) as the forecasting method. Aggregate planning is also conducted for better production planning. The results of aggregate planning provide solutions to increase the workforce to balance production capacity by the number of demands. Squared Coefficient of Variation (SCV) calculations indicates the demand follows a static pattern. Therefore, the appropriate lot sizing method is the Economic Order Quantity (EOQ) to carry out the production needs. Finally, this paper uses capacity planning using Rough-Cut Capacity Planning (RCCP) and Capacity Requirement Planning (CRP) methods. As a result, the capacity meets the Master Production Schedule (MPS) as well as MRP and they are feasible to be implemented.

Keywords: ABC classification, Inventory control, Capacity planning.

1 | Introduction

As technology advances in the field of industry, of course, it will lead to intense competition in the business world. The company will do various ways to satisfy the consumer by trying to produce a high-quality product [1] with a competitive price, provide a good service [2] and the timeliness in the delivery. Real-time demand data could further improve the timeliness of deliveries and reduce inventory levels [3]. Hence, the company needs to run an effective production system by making excellent planning and control start from managing the raw material inventory to the valuable final product [4]. Inventory is the stock of any goods or resources used in a company or organization. The inventory system is a set of policies and controls that are used in production and logistics networks to coordinate supply cycles overseeing the level of inventory to be refilled, the number of orders that must be regulated to reduce risks associated with uncertainty [5], [6]. All manufacturing industries must have a supply of raw materials for production needs.

Corresponding Author: filscha.nurprihatin@sampoernauniversity.ac.id

http://dx.doi.org/10.22105/riej.2021.306872.1250

The importance of inventory management in industrial applications derives from the effect of out-of-stock in the levels of customer satisfaction and the impact of stock in the economic balance of companies [6]. It is also useful to satisfy safety requirements, in cases where the availability of hazardous raw materials can be replaced with inventory of its products [6]. Furthermore, inventory also plays an important role in the coordination of maintenance turnarounds between various facilities across a site [6].

This research is conducted in the company producing the instant noodle. The manufacturing industry produces a wide range of brands and flavor variants. The company has 6 brands of products with 18 flavors. Instant noodle consists of some raw materials such as raw noodle that comes from flour. Flour is the main raw material in the instant noodles manufacturing, along with spices, seasoning oil, and package which are the compilers and complementary materials. A real-world problem may deal with an inventory shortage [7]. Currently, the company still have the raw materials issue caused by the delay in raw materials receipt (backlog) and the realization of the delivery of raw materials is not following the planned number. This condition implies the overstock and losses on high costs incurred. The backlog and overstock data for all 18 flavor variants in 2017 are shown in *Fig. 1*.

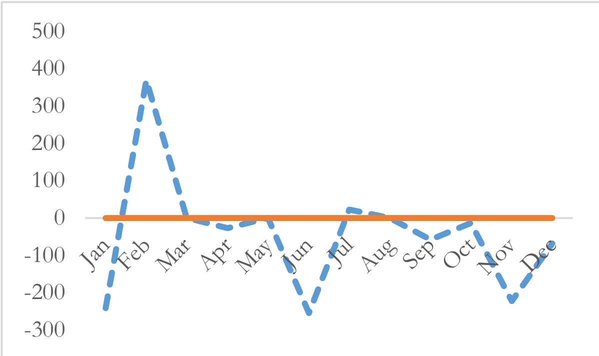

Fig. 1. Backlog and overstock.

The previous research showed that the over-supply or over-demand should be avoided and recommended a strong need for a precise forecasting [8]. In the supply chain, it is assumed that each member of the chain owns a warehouse and uses a specific replenishment policy to control inventory to meet the demands of its customers appropriately [9]. To address the mismatch between supply availability, service time, and demand in integrated production networks, inventory is held at different stages of the process [6], [10], [11]. The uncertainties increase the required practical production planning decisions [12]. However, in practice warehouses are actually managed in terms of policies, which are simple rules that dictate when to replenish an inventory with the corresponding amount [10]. The inventory policies considered are the (r,Q) and (s,S) policies [10]. On one hand, the (r,Q) inventory policy and order for Q units is placed every time the inventory level reaches level r [10] to minimize the expected cost of replenishment and out-of-stock [6]. On the other hand, the (s,S) policy the inventory is reviewed in predefined intervals [10].

Previous research utilized Material Requirement Planning (MRP) as the predetermined input by ant colony optimization to improve manufacturing performance [13]. The good manufacturing performance means to produce items with satisfactory and superior quality, accelerate delivery time and offer excellent after-sales service [13].

In short, it is important to make sure the production flow on the shop floor is streamlined. The raw material should be treated as an economical commodity, so the improvement related to the raw material is never ignored by the whole supply chain stakeholders.

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2 | Literature Review

A previous study suggested to utilize the green manufacturing including the inventory control process to achieve environmentally-friendly activities and achieve better performance as well [14]. The ABC classification is an effective technique to develop a mechanism for identifying inventory items that not only has a significant impact on the total inventory cost [15]. This technique classifies items into three classes, A, B, and C depends on certain characteristics. Previous research utilized the ABC classification in dynamic storage assignment problem and used the order frequency as the criterion [16]. Meanwhile, a research classified them according to the item's annual consumption value [17]. Another paper classified the inventories into A, B, and C types, based on picking frequency [18]. In this paper, a percentage of stored goods are used.

Several studies combined and improved this technique. A study improved this technique in determining weights using Shannon entropy [15]. A periodic review policy based on the ABC classification was conducted in order to control the raw materials inventory [17].

Since the expected service time is normally much smaller than the production lead time, the demand of a customer must be anticipated through a forecast [10]. An accurate forecast results in establishing appropriate operational practices where the forecast inaccuracies have significant implications [19]. But, the main difficulty is that a forecast is an estimation since demands are uncertain [10], which leads to both out-of-stock and excessive stock situations [20].

This uncertainties issue has been tackled through stochastic programming model to point out the nature of inventory policy [6]. Seasonal future demand was estimated using the multiplicative seasonal method [12]. Previous study tried to estimate and predict the demand of new product through machine learning [21]. Other study presented a forecasting model to estimate the demand based on big data technologies [22]. Three stages were used such as a cluster analysis to classify traffic patterns, and a relational analysis to identify influential factors, and a decision tree to establish classification criteria [22]. Other study utilized the Root Mean Squared Error (RMSE) to measure the demand accuracy [8], while this paper use Mean Absolute Percentage Error (MAPE), Mean Absolute Deviation (MAD), and Mean Squared Deviation (MSD) at the same time.

Aggregate planning is a fundamental decision model in supply chain management, refers to the determination of production, inventory, capacity and labor usage levels in the medium term [23]. In general, the benefits of inventories derive from their ability to reduce the interdependence of processing units, to mitigate the effects of bottlenecks, and to facilitate capacity utilization [6]. In this paper, the demand as well as the production capacity for this aggregate product in different periods of the planning horizon is given [11]. To plan the aggregate accurately, the first decision is the detail forecasts of each product [21]. One challenge we must address that arises from this decision is how to apply inventory constraints [21], such as production and resources capacity [6]. An aggregate planning model is developed to balance the demand and production capacity simultaneously [11]. The aggregate planning should make sure the objective and the constraints are satisfied by adjusting output rates, inventory levels, backorders and the other controllable variables [11]. The controllable variables are inventory costs, ordering costs, training costs, and worker hiring and firing costs [24]. Another study added some important variables such as transportation cost of the vehicles and the energy cost to keep the cold storage temperature [25]. These variables are the important factors in terms of conversion of raw materials into final products, their maintenance, and distribution to end customers [26]. Therefore, aggregate planning plays a major role in shaping the Master Production Scheduling (MPS) and consequently the shop floor scheduling operations [27].

MPS is generally specifies the production quantity of each finished good during each planning horizon period of multiple weeks and is based on estimated or known demands [20], [28]. The MPS is constrained by the decisions regarding capacity and the targets in terms of inventory levels [29]. To be able to cope with the differences between the forecast and the actual orders, overtime is allowed [29]. Since overtime is limited, we also consider backorders as well ensuring feasibility [29]. Because MPS does not plan product types but product family, the target inventory level has to be disaggregated [29].

Although other research tried to integrate the aggregate production planning and MPS [29], this paper solve them gradually. This paper constantly pay attention to the quality of solution by making sure they are feasible to run in minimizing inventory costs [30].

Making good use of the material requirements plan result can increase inventory turnover, improve procurement quality, increase productivity, and increase customer satisfaction [13]. As a result, the rapid and correct implementation of the material requirement plan will have a better effect on the efforts of the whole company [13].

According to the structure of the MRP system, it must complete the following three main functions: parts demand calculation, inventory calculation, and purchase calculation [13]. By using product structure (of the raw material list, product material list) and the scheduled completion date of each component combination, the MRP system could complete these three functions after getting the amount of product demand [13]. To accomplish these three functions, the input items of the MRP system are product structure, inventory status, lot sizing rule, and Master Production Schedule (MPS) [13]. The output items are the number of components that should be ordered, the capacity demands and the manufacturing demands [13].

The demand deployment of the MRP system is based on the final project [13]. It calculates from top to bottom and traces back from the bottom to top to meet the production of the final project and obtains the number of components needed [13].

In the MRP system, the material requirement file is established for each item of the main production schedule, and the final product requirement in MPS is converted to the gross requirement [13]. The net requirement is calculated from the gross requirement [13]. Then, the planned order receipts for each period of the total product or material are obtained by production or purchase, and the lot size of each item in each period must be calculated by the batch rule [13]. The planned order quantity for each period of the material item is equal to the planned order quantity for each period of the material item unless the lead time for each period of the material item is non-zero [13]. The gross demand at the next level of the structure is determined by the number of planned orders issued during each period of the material items [13].

Bill of Material (BOM), also known as the product structure table or material structure, which is the most paramount foundation to compose the product information [13]. It records all parts of the component and interrelated information of a product, such as the kind of component and the required quantity to meet the final production from the BOM [13]. Generally, BOM data contain various attributes such as part number, quantity, and specification, etc. [13].

The Squared Coefficient of Variation (SCV) calculations are utilized to measure the variability of the demand pattern. SCV formula can be seen in the *Eq. (1)* [31]. If SCV < 0.2, use a simple EOQ and utilize a heuristic if $SCV \geq 0.2$ [31]. The total cost can be obtained from *Eq. (2)* [32].

$$\text{SCV} = \frac{\text{Variance of demand per period}}{\text{Square of average demand per period}}. \quad (1)$$

$$\text{Total cost} = (\text{D})(\text{C}) + \left(\frac{\text{D}}{\text{Q}^*}\right)(\text{S}) + \left(\frac{\text{Q}^*}{2}\right)\text{H}. \quad (2)$$

where:

D: Annual demand of the product.

C: Cost per unit of product.

Q*: EOQ.

S: Fixed cost incurred per order.

H: Holding cost per unit per year.

3 | Research Methodology

This paper tries to solve the problem of excess or shortage of raw materials through serial stages, starting from the ABC classification, along with forecasting, aggregate planning, and capacity planning. ABC analysis is a technique for prioritizing the management of inventory as shown in *Fig. 2*. Inventories are categorized into three classes - A, B, and C. Most management efforts and oversights are expended on managing A items while C items get the least attention and B items are in-between [33]. Forecasting predicts the demands which are a crucial step in production planning schedule to satisfy customer needs on time [34]. At this stage, the Holt-Winters exponential smoothing is used as an appropriate and popular approach for predicting seasonal time series. The discussion continues on the aggregate planning stage. Aggregate planning is a process which helps companies to provide better service level with smaller preparations, to shorten customer lead times, to stabilize production levels, and to give control from top management in managing the business [5]. MPS is a production planning with a planned time to produce each finished product [5]. The production capacity is closely related to the MPS, which describes what and how many items should be produced in a given period. The problem that often occurs is a delay in raw material shipment. This is due to the lack of careful planning for the production process. To overcome these problems, we require production capacity planning using Rough Cut Capacity Planning (RCCP). RCCP is the second priority in the planning hierarchy, and is used to evaluate the resource usage of the MPS [35]. Material Requirements Planning (MRP) is a well-known approach to inventory management of dependent demand items. Items that are independently demanded are typically finished goods, while dependently demanded items are typically components and subassemblies that are related to an end item by a BOM [13]. CRP is increasingly close to the success of planning and capacity measurement due to the existence of time standards and route information settings. CRP usually does not provide information to change the MPS because it is easier to change capacity by using overtime, subcontract and additional manpower. At the end, the objective function is to minimize the cost [11]. The two types of data used in this research are primary and secondary data. The primary data was obtained verbally in the interview session with the supervisor, mentor, operators, and administrators. The secondary data was obtained from written documents such as company data, companies' documents, journals, articles, and others.

4 | Result and Discussion

In this section, the discussion covers the ABC classification and followed by the most appropriate forecasting method. After that, aggregate planning is performed before heading to the stage of making a MPS. The production capacity at the MPS stage will be checked using Rough-Cut Capacity Planning (RCCP). The output from the MPS is treated as the input for MRP. The production capacity on the MRP is then checked using the Capacity Requirement Planning (CRP).

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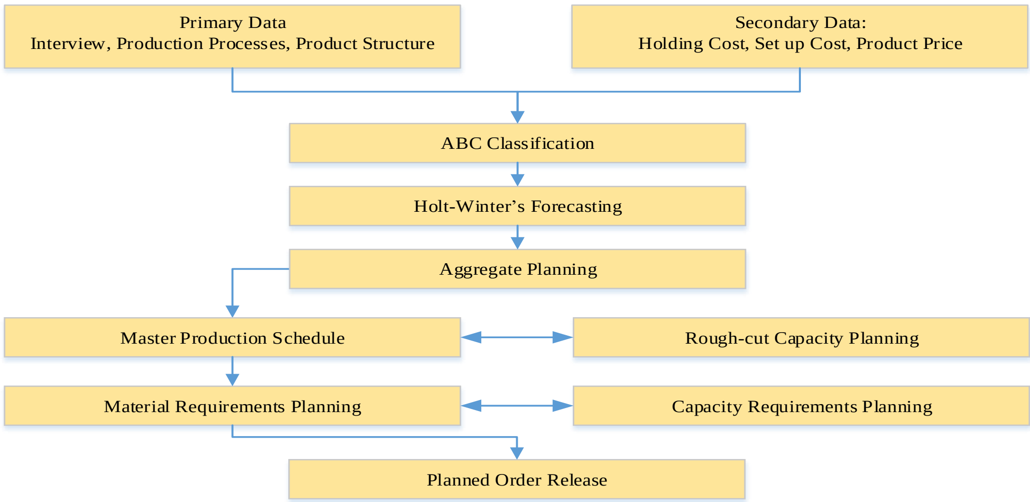

Fig. 2. Research flow chart.

4.1 | ABC Classification

There are 18 product variants and four of them are classified as the "A" category, coded in IGB, ISM, IAB, and IKA as shown in *Table 1*. These items are classified as the "A" category because they serve 20% of storage. Six items coded in IGRS, PMAB, PMBS, IKALA, and ISL are classified as the "B" category since the company holds them as 30% of the whole inventory. Finally, the rest are classified as the "C" items as they occupy 50% of the storage. Hence, the attention in terms of inventory is focused on the "A" category. Later, these items are forecasted to predict their future demand.

Table 1. ABC classification result.

No.	Flavor Variants	Available Inventory	Percentage of Stored Goods
1	IGB	19200	20%
2	IAB	16400	
3	ISM	14600	
4	IKA	10800	
5	IGRS	9600	30%
6	PMAB	4480	
7	PMBS	3920	
8	IKALA	7200	
9	ISL	7000	
10	MTK	5400	50%
11	SAB	4788	
12	SUSD	3564	
13	SAK	2142	
14	PMMAB	2415	
15	SUAB	1836	
16	SUGOPANG	1404	
17	SAGOR	750	
18	SAKBS	300	
Total		115799	

4.2 | Holt-Winters Forecasting Analysis

The historical data patterns on each product can be seen from *Fig. 3* to *Fig. 6*. June and December are the common peak seasons in all the "A" products. In detail, the data pattern for product IGB has peak seasons in March, June, and December as shown in *Fig. 3*. *Fig. 4* tells us the peak seasons for product IAB are in May, June, September, November, and December. Meanwhile, product ISM has only peak seasons in two months, which are June and December as manifested in *Fig. 5*. Lastly, *Fig. 6* denotes the peak seasons for product IKA in five months, such as February, May, June, November, and December. Besides, in terms of trend analysis, these products also indicate uptrend throughout the year. Therefore, this paper proposes that the forecasting method should consider seasonality and trend conditions. A previous study have shown that the Holt-Winters exponential smoothing method is able to provide suitable forecasts on seasonal and trend demand patterns [36]. This paper also presents the Holt-Winters exponential smoothing as an appropriate method. This paper runs nine different scenarios in terms of smoothing constant, as shown in *Table 2*. It turns out that different smoothing constant works divergently. The results show that product IGB, IAB, and IKA performs well with the smoothing constant $a = 0.9$, $\gamma = 0.1$, $\beta = 0.1$. The performance indicator is MAPE and MAD. Regarding these three products, the forecasted data fluctuates with the higher α results in the smaller MAPE and MAD. The other product, which is ISM, fits with the smoothing constant $a = 0.1$, $\gamma = 0.1$, $\beta = 0.1$ and follows the lower α results in the smaller MAPE and MAD. *Table 3* refers the forecasting results that have been selected based on the most suitable smoothing constant on the product IGB, ISM, IAB, and IKA. These data are the inputs for aggregate planning stage.

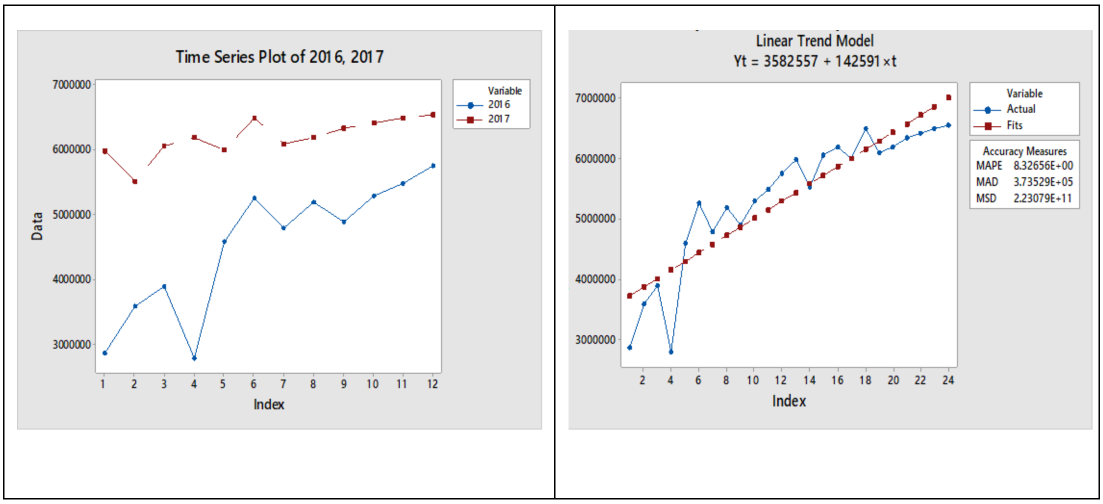

Fig. 3. Seasonal pattern and trend analysis for IGB.

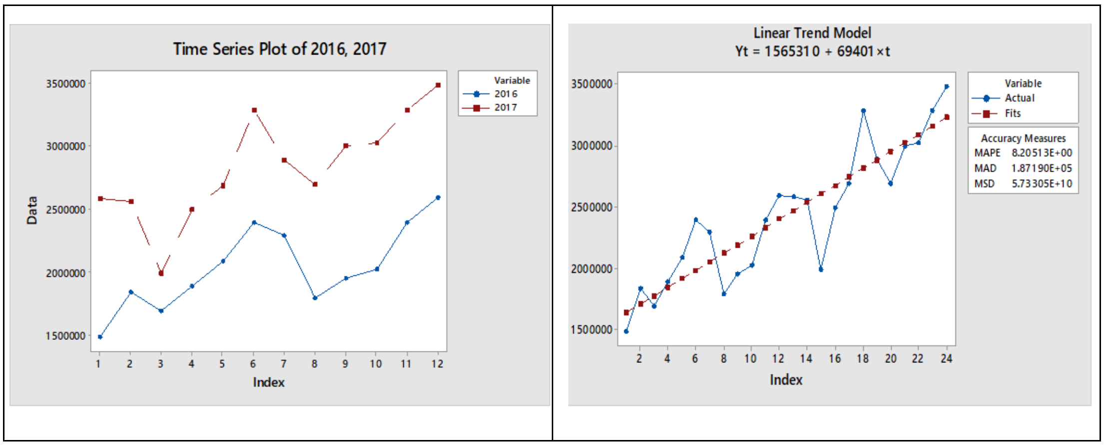

Fig. 4. Seasonal pattern and trend analysis for IAB.

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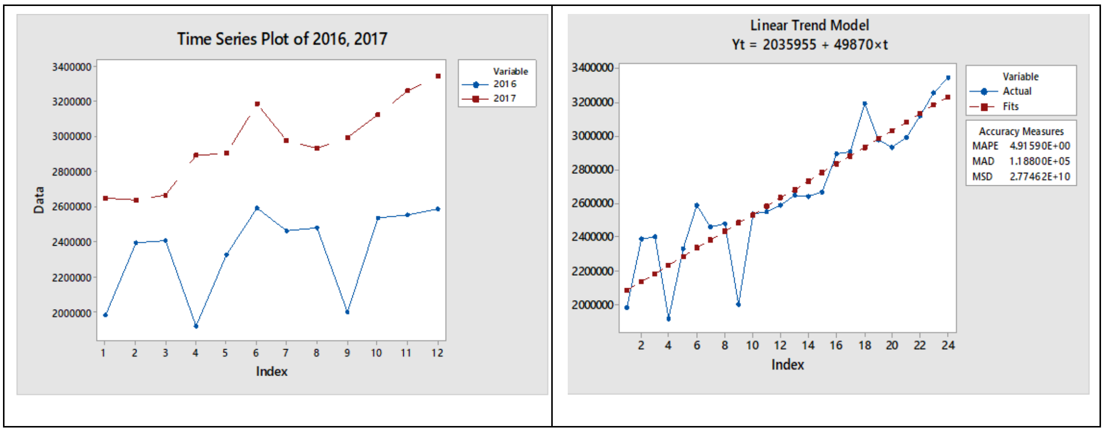

Fig. 5. Seasonal pattern and trend analysis for ISM.

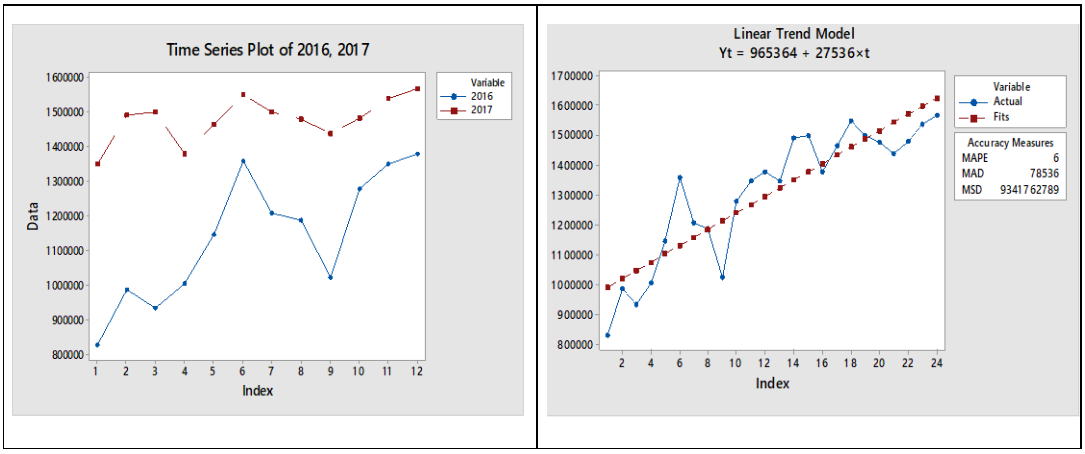

Fig. 6. Seasonal pattern and trend analysis for IKA.

Table 2. Smoothing constant scenarios.

Scenario	Smoothing Constant	Fit for Specific Product
1	α = 0.1 γ = 0.1 β = 0.1	ISM
2	α = 0.2 γ = 0.1 β = 0.9	
3	α = 0.3 γ = 0.9 β = 0.1	
4	α = 0.4 γ = 0.9 β = 0.9	
5	α = 0.5 γ = 0.1 β = 0.1	
6	α = 0.6 γ = 0.1 β = 0.9	
7	α = 0.7 γ = 0.9 β = 0.1	
8	α = 0.8 γ = 0.9 β = 0.9	
9	α = 0.9 γ = 0.1 β = 0.1	IGB, IAB, IKA

Table 3. Forecasting results.

Month	Forecast 2018 Products and Flavor Variants			
	IGB	ISM	IAB	IKA
January	5060530	2881919	2527841	1233181
February	5226143	3156213	2755404	1403308
March	5725059	3199771	2326878	1379124
April	5136889	3039112	2779493	1358891
May	6138679	3334205	3052584	1492097
June	6836712	3705005	3648850	1668667
July	6340171	3509641	3354610	1554897
August	6659845	3514955	2908532	1533844
September	6573141	3251536	3229894	1417749
October	6879614	3720932	3318849	1597274
November	7058026	3841887	3758560	1674710
December	7271099	3947656	4041331	1713318

4.3 | Aggregate Planning

After performing the forecasting analysis, the next step is to conduct the aggregate planning. This step aims to plan production quantities based on forecasting results and to determine the number of workers to minimize related costs production. At this stage, this paper performs linear programming to produce the global optimal aggregate planning subject to cost structure as shown in *Table 4*. From there, the process proceeds to the total cost calculation for 1 year ahead. The total cost for product IGB, IAB, ISM, and IKA are IDR 143,010,336,000, IDR 71,604,692,000, IDR 77,286,664,000, and IDR 34.385.446.000 respectively.

Table 4. Cost structure.

Cost (IDR)	
Regular Cost	5500000/month
Overtime	230000/overtime
Hiring	500000/hiring
Layoff	3000000/layoff
Inventory Cost	100/pcs
Backorder	800/pcs
Cost of Goods Sold	2000/pcs
Subcontract	2200/pcs

4.4 | MPS and RCCP

The succeeding stage is to create a MPS which will be implemented based on the production lot sizes and the remaining stock from the previous period. In this paper, the MPS is made for 52 weeks from January to December 2018. *Table 5* shows the MPS raw data of each flavor variant. *Table 6* denotes an example of the calculation for the IGB flavor variant.

Table 5. MPS data.

Product	IGB	ISM	IAB	IKA
Lead Time	0	0	0	0
On Hand	3538490	2550000	1977690	898087
Lot Size	1000000	500000	500000	250000

The MPS is further tested with the RCCP method to check the feasibility and make headway to the MRP stage. If the RCCP results in the available capacity are greater than the required capacity, it means MPS deserves to be continued to the MRP stage. For simplicity, the calculation is done only for IGB at this stage. For the first six months, *Table 7* presents its available capacity while *Table 8* and *Table 9* together point its required capacity using two different approaches. *Table 8* and *Table 9* utilize the Capacity Planning Overall Factor (CPOF) and Bill of Labor Approach (BOLA) respectively. Altogether, the favorable outcome shows the capacity available for IGB, ISM, IAB, and IKA is satisfactory, indicates the MPS is feasible to run.

4.5 | Material Requirements Planning and CRP

Based on the forecasting results, the SCV calculations are performed to measure the variability of the demand pattern. SCV formula can be seen in *Eq. (1)* [31]. *Table 10* shows the future demand for all "A" items are static because of SCV < 0.2, meaning the EOQ method can be applied.

IGB has four components of raw materials at once forming its BOM such as TPG, ETK, BM, and MBM, as presented in *Fig. 7*. *Table 11* shows the cost of MRP calculation results. TPG is processed through the serial process on work station 1B, 2B, 3B, 4B, 5B, 6B, and 3A. ETK processing is completed by using work station 2A, while BM and MBM go to work station 1A. The highest EOQ is presented

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by ETK as it has the highest total inventory. From the total cost point of view, MBM denotes the highest value.

Table 6. MPS calculation for January and February.

Month (2018)	Past	January				February			
Week		1	2	3	4	5	6	7	8
Sales Forecast		1265133	1265133	1265132	1265132	1306536	1306536	1306536	1306535
Actual Orders		1645850	1645850	1645850	1645850	1599748	1599748	1599748	1599748
Projected Available Balances (PAB)	3538490	3538490	1892640	246790	600940	955090	355342	755594	155846
Available to Promise (ATP)				600940	955090	355342	755594	155846	556098
MPS				1399060	1044910	644658	1244406	844154	1443902
MPS with LS				2000000	2000000	1000000	2000000	1000000	2000000

Table 7. Available capacity for IGB.

Work Center (WC)	Month (Working Days)					
	January (26)	February (23)	March (25)	April (24)	May (24)	June (20)
WC-1 (units)	2742.01	2425.63	2636.55	2531.09	2531.09	2109.24
WC-2 (units)	1371.01	1212.81	1318.28	1265.54	1265.54	1054.62
WC-3 (units)	2742.01	2425.63	2636.55	2531.09	2531.09	2109.24
WC-4 (units)	1371.01	1212.81	1318.28	1265.54	1265.54	1054.62
WC-5 (units)	2742.01	2425.63	2636.55	2531.09	2531.09	2109.24
WC-6 (units)	5484.02	4851.25	5273.10	5062.18	5062.18	4218.48
WC-7 (units)	2742.01	2425.63	2636.55	2531.09	2531.09	2109.24

Table 8. Required capacity for IGB using CPOF.

Work Center (WC)	Historical Proportion	Month (Working Days)					
		January (26)	February (23)	March (25)	April (24)	May (24)	June (20)
WC-1	0.22	950	1425	1425	1187.5	1425	1662.5
WC-2	0.03	111.11	166.67	166.67	138.89	166.67	194.44
WC-3	0.21	888.89	1333.33	1333.33	1111.11	1333.33	1555.56
WC-4	0.01	55.56	83.33	83.33	69.44	83.33	97.22
WC-5	0.20	833.33	1250	1250	1041.667	1250	1458.33
WC-6	0.20	833.33	1250	1250	1041.667	1250	1458.33
WC-7	0.13	555.56	833.33	833.33	694.44	833.33	972.22

Table 9. Required capacity for IGB using Bill of Labor Approach (BOLA).

Work Center (WC)	Historical Proportion	Month (Working Days)					
		January (26)	February (23)	March (25)	April (24)	May (24)	June (20)
WC-1	0.010	950	1425	1425	1187.5	1425	1662.5
WC-2	0.001	111.11	166.67	166.67	138.89	166.67	194.44
WC-3	0.009	888.89	1333.33	1333.33	1111.11	1333.33	1555.56
WC-4	0.001	55.56	83.33	83.33	69.44	83.33	97.22
WC-5	0.008	833.33	1250	1250	1041.67	1250	1458.33
WC-6	0.008	833.33	1250	1250	1041.67	1250	1458.33
WC-7	0.006	555.56	833.33	833.33	694.44	833.33	972.22

MRP needs to be verified whether the number of orders with the existing lead time satisfactory or not. If the available resource capacity is greater of the required capacity, then MRP can be implemented, as shown in *Table 12*.

Table 10. SCV results.

	IGB	IAB	ISM	IKA
Variance of Demand per Period	$(5.59)(10^{11})$	$(2.43)(10^{11})$	$(1.03)(10^{11})$	$(2.00)(10^{10})$
Squared of Average Demand per period	$(3.90)(10^{13})$	$(9.87)(10^{12})$	$(1.17)(10^{13})$	$(2.26)(10^{10})$
SCV	0.014	0.025	0.009	0.009

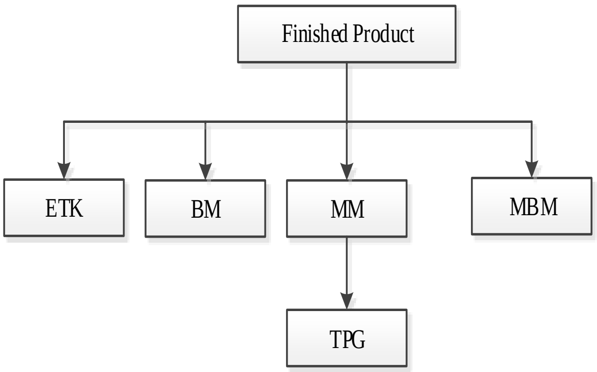

Fig. 7. Product structure.

Table 11. Total inventory costs for IGB.

Component Name	W C	EOQ	Total Inventory	Total Planned Order	Material Cost (Rp)	Ordering Cost (Rp)	Holding Cost (Rp)	Total Cost (Rp)
TPG	1B	612	21374	11628	1,150	12,500	800	30,708,900
	2B							
	3B							
	4B							
	5B							
	6B							
	3A							
ETK	2A	122,720	35,698,000	75,000,000	250.	10,000	100	22,320,300,000
BM	1A	86,780	35,360,000	75,000,000	350	10,000	200	33,322,500,000
MBM	1A	86,780	35,360,000	75,000,000	400	10,000	200	37,072,500,000

Table 12. CRP for IGB.

Work Center	Capacity	Months (Working Days)					
		January (26)	February (23)	March (25)	April (24)	May (24)	June (20)
1B	Available	2742.012	2425.626	2636.55	2531.088	2531.088	2109.24
	Required	1666.875	1190.625	1428.75	1428.75	1428.75	1666.875
2B	Available	1371.006	1212.813	1318.275	1265.544	1265.544	1054.62
	Required	198.8194444	142.0138889	170.4166667	170.4166667	170.4166667	198.8194444
3B	Available	2742.012	2425.626	2636.55	2531.088	2531.088	2109.24
	Required	1559.930556	1114.236111	1337.083333	1337.083333	1337.083333	1559.930556
4B	Available	1371.006	1212.813	1318.275	1265.544	1265.544	1054.62
	Required	101.5972222	72.56944444	87.08333333	87.08333333	87.08333333	101.5972222
5B	Available	2742.012	2425.626	2636.55	2531.088	2531.088	2109.24
	Required	1462.708333	1044.791667	1253.75	1253.75	1253.75	1462.708333
6B	Available	5484.024	4851.252	5273.1	5062.176	5062.176	4218.48
	Required	1462.708333	1044.791667	1253.75	1253.75	1253.75	1462.708333
3A	Available	2742.012	2425.626	2636.55	2531.088	2531.088	2109.24
	Required	976.5972222	697.5694444	837.0833333	837.0833333	837.0833333	976.5972222
2A	Available	1828.008	1617.084	1757.7	1687.392	1687.392	1406.16
	Required	441.875	315.625	378.75	378.75	378.75	441.875
1A	Available	1828.008	1617.084	1757.7	1687.392	1687.392	1406.16
	Required	927.5	662.5	795	795	795	927.5

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5 | Conclusion

The ABC classification results of 18 taste variants are IGB, ISM, IAB, and IKA for class A with the percentage of goods saved by 20%. IGRS, PMAB, PMBS, IKALA, and ISL for class B with the percentage of goods stored by 30%. MTK, SAB, SUSD, SAK, PMMAB, SUAB, SUGOPANG, SAGOR and SAKBS for class C with the percentage of goods stored at 50%. So, the attention and the inventory control are preferred for class "A" namely IGB, ISM, IAB, and IKA. The forecasting method is applied using Triple Exponential Smoothing (TES) because the data has a trend and seasonal with the smallest error rate that is $a = 0.9$, $\gamma = 0.1$ and $\beta = 0.1$ for three products, such as IGB, IAB, and IKA. The value of $a = 0.1$, $\gamma = 0.1$ and $\beta = 0.1$ is fit for ISM. The results of aggregate planning can run efficiently while balancing the workforce and the amount of production. The aggregate planning indicates that the company should require a lot workforce to balance the amount of production with the production capacity of labor. The total cost for product IGB, IAB, ISM, and IKA are IDR 143,010,336,000, IDR 71,604,692,000, IDR 77,286,664,000, and IDR 34.385.446.000 respectively. RCCP under CPOF and BOLA both indicates that MPS is feasible to be implemented because the available capacity in each production line is enough to fulfill the required demand. RCCP is based on MPS lot size data with lot size already according to the lot size determined by the 52 weeks made up to 12 months, machine time processing data and historical proportions machine. Based on the SCV analysis and calculations, Economic Order Quantity (EOQ) is the selected lot-sizing technique to perform the MRP calculation. The CRP result shows the MRP is feasible for product all "A" products. CRP is based on planned order release data from MRP each raw material for 52 weeks which is made 12 months based on lot size, data setup time, run time, operation time and setup time/lot size.

Future study could utilize the regression tree since it was claimed more effective than other regression methods in predicting demand [21]. Under uncertainty where statistical data are either not that reliable or not even available, MPS model can be developed [37] as one of the unique characteristics in the further study.

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E-ISSN: 2717-2937 | P-ISSN: 2783-1337

International Journal of Research in Industrial Engineering

IJRIE

www.riejournal.com

Int. J. Res. Ind. Eng. Vol. 10, No. 4 (2021) 346–357.

Paper Type: Research Paper

Application of Accelerated Life Testing in Human Reliability Analysis

Rasoul Jamshidi[1],*, Mohammad Ebrahim Sadeghi[2]

[1] Faculty of Engineering School, Damghan University, Semnan, Iran; r.jamshidi@du.ac.ir.

[2] Faculty of Management, Department of Industrial Management, University of Tehran, Tehran, Iran; sadeqi.m.e@gmail.com.

Citation:

Jamshidi, R., & Sadeghi, M. E. (2021). Application of accelerated life testing in human reliability analysis. *International journal of research in industrial engineering, 10* (4), 346-357.

Received: 28/05/2021 Reviewed: 08/07/2021 Revised: 22/10/2021 Accepted: 17/10/2021

Abstract

As manufacturers and technologies become more complicated, manufacturing errors such as machine failure and human error have also been considered more over the past. Since machines and humans are not error-proof, managing the machines and human errors is a significant challenge in manufacturing systems. There are numerous methods for investigating human errors, fatigue, and reliability that categorized under Human Reliability Analysis (HRA) methods. HRA methods use some qualitative factors named Performance Shaping Factors (PSFs) to estimate Human Error Probability (HEP). Since the PSFs can be considered as the acceleration factors in Accelerated Life Test (ALT). We developed a method for Accelerated Human Fatigue Test (AHFT) to calculate human fatigue, according to fatigue rate and other effective factors. The proposed method reduces the time and cost of human fatigue calculation. AHFT first extracts the important factors affecting human fatigue using Principal Component Analysis (PCA) and then uses the accelerated test to calculate the effect of PSFs on human fatigue. The proposed method has been applied to a real case, and the provided results show that human fatigue can be calculated more effectively using the proposed method.

Keywords: Error, Accelerated life testing, Human fatigue, Maufacturing.

1 | Introduction

Today we see comprehensive automation and consequently the reduction of the human role in most manufacturing systems. Although these efforts reduce human error and increase product quality, humans still have an important effect on quality in manufacturing systems. Human factors (i.e., fatigue, recovery) can have a significant impact on the performance of the overall system [1].

In order to prevent or reduce human fatigue and disorders, human reliability and its related issue are studied and investigated in manufacturing contexts such as design work process, equipment design, and ergonomic consideration. Battini et al. [2] proposed that human disorder is one of the important causes of health problems in workers. Different methods have been proposed to mitigate the human disorders in manufacturing systems.

Corresponding Author: r.jamshidi@du.ac.ir

http://dx.doi.org/10.22105/riej.2021.288263.1227

Some methods highlighted the workplace design and environmental conditions [3] and [4], and other methods investigated the work redesigning and redefining [5]. The common point of all these methods is that some important factors such as human reliability and fatigue should be measured in order to evaluate the severity of the effect on quality and cost. Other studies investigated the human reliability calculation methods such as the first and second generation of HRA and introduced new concepts such as fatigue in HRA.

HRA methods are time consuming, and new methods must be introduced to reduce the implementation cost and time. In this paper, we propose a hybrid method that uses the advantage of ALT as a reliability analysis model to predict the fatigue value. The effective parameters on human fatigue are also extracted by PCA. This hybrid method reduces the time and costs in HRA.

2 | Literature Review

There are several sources of human error; one of them is fatigue that stems from other factors; in fact, every loss caused by psychological or physiological effort is named fatigue that has several symptoms. Lack of energy, physical exertion [6], lack of motivation [7], and sleepiness [8] are the symptoms of fatigue. Human fatigue commonly disrupts human performance and leads to undesirable costs to the manufacturer such as quality cost, maintenance cost, etc. With unfavorable effects on judgment, efficiency, and productivity [9].

Many researchers investigated fatigue in qualitative and quantitative categories. In the first category, they studied the effective factors in human fatigue, such as the type of work, environmental condition, and human body specification [10] and [11].

The second category investigated the methods to calculate the fatigue value due to qualitative factors. Also, some papers in this category proposed different methods for human fatigue recovery. [12]-[14] proposed several methods to calculate the fatigue based on some factors such as Maximum Holding Time (MHT) and Maximum Endurance Time (MET). Imbeau and Farbos [15] proposed the static fatigue analysis through the concept of MET, which defines the maximum time a muscle can sustain a load. Ma et al. [16] studied the influence of external load on human fatigue in a real-time situation. Fruggiero et al. [17] investigated the imposed uncertainty due to human error. Peternel et al. [18] proposed two fatigue management protocols to calculate and reduce human fatigue. Li et al. [19] introduced the fatigue causal network for fatigue management.

Since the first proposed methods for fatigue measuring only consider the work type and some human specifications, PSFs have been proposed to increase the accuracy of fatigue calculation.

The term PSF encompasses the various factors that affect human performance and can change the HEP. Although many methods use PSFs, there is not a standard set of PSFs that are used for most HRA methods [20]. There are about 60 PSFs, with varying degrees of overlap [21]. Boring studied the important PSFs and proposed 8 PSFs that are considered in common HRA methods [22], such as stress, complexity, ergonomics and etc. Also, the PSFs affect human fatigue/recovery and should be considered in human fatigue quantification. Rasmussen and Laumann [23] proposed a method to evaluate fatigue as a performance shaping factor in the Petro-HRA method.

Some researchers studied human fatigue from the perspective of reliability and believed that human fatigue could be investigated using reliability methods [24]. In fact, they considered human as a machine and proposed some reliability and maintenance policy to mitigate the human failure rate. For example Mahdavi et al. [25] proposed a mathematical model for a dynamic cellular manufacturing systems whit human resources. Cappadonna et al. [26] addressed the machine scheduling problem with limited human resources. Taylor [27] studied the human as an important resource in maintenance actions. The main problem to study human fatigue by machines reliability methods is that the PSFs have not been considered by reliability methods. Griffith and Mahadevan [28] investigated the effect of fatigue on human reliability.

ALT can be used to consider the PSFs in reliability assessment methods and evaluate human fatigue. ALT is the process of testing an element subjecting it to environmental conditions such as stress, temperatures [29] and [30]. PSFs can be considered as an Accelerated Factor (AF) to calculate human fatigue. In fact, ALT reduces the time and cost of human fatigue calculation.

To the best of author's knowledge, there is no a research in which studied human fatigue using ALT and compared its result with common fatigue models. In this paper, we propose an Accelerated Life Test (ALT) to calculate the human fatigue value to consider the effect of PSFs in fatigue calculation and make fatigue value closer to reality. To find the most effective PSFs we utilize Principal Component Analysis (PCA) since the ALT needs a limited number of factors. Also, a real case will be investigated to examine the effectiveness of the proposed methods. In other words, we select the most effective PSFs with PCA and then calculate the fatigue by ALT. this method reduces the time and decreases the cost of human fatigue calculation. Also, eliminating unnecessary PSFs reduces the data gathering process without significant prediction error.

3 | Research Methodology

In the proposed method, we first select the most effective PSFs on human fatigue using the PCA method. By PCA, we can limit the PSFs and consider the important PSFs to facilitate the data gathering. After selecting the PSFs, we use the ALT to evaluate the effect of PSFs on human fatigue. Using ALT, we can calculate the fatigue according to the PSfs value with a non-significant error.

3.1 | Principal Component Analysis (PCA)

PCA is an unsupervised exploratory method for feature extraction.This method combines several input variables in a specific way to drop the "least important" variables and retains the most valuable parts of all of the variables. PCA produces orthogonal components by decomposing the initial input variables matrix [31].

PCA is mostly used for making predictive models. PCA can be done based on the covariance matrix as well as the correlation matrix, and data matrix using eigenvalues and eigenvectors. The data matrix should be normalized until having zero mean and unit variance [32]. The results of a PCA are usually studied in terms of component scores, or factor scores. The steps of PCA implementation for some stochastic vector X is as follows:

I. Consider we have a matrix X with n rows and p+1 columns, where there is one column corresponding to the dependent variable (usually denoted Y) and p columns corresponding to each of independent variables.
II. For each column, subtract the mean of that column from each entry.
III. Make the matrix Z by standardizing each column of X to make sure each column has mean zero and standard deviation 1.
IV. Calculate the Z^TZ.
V. Calculate the eigenvectors and eigenvalue for Z^TZ.
VI. Take the eigenvalues $\lambda_1, \lambda_2, \ldots$ and sort them from largest to smallest.
VII. Calculate the proportion of variance explained by *Eq. (1)* for each input variable.

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$$\text{proportion of variance explained}_i = \frac{\lambda i}{\sum_{i=1}^{n} \lambda i}. \quad (1)$$

VIII. For each variable, pick a threshold and add input variables until the cumulative proportion of variance hits that threshold.

IX. Select the last input variable that hits the threshold and its previous variable as effective inputs variable on Y.

Using PCA in human fatigue analysis, we can eliminate the probable dependency between PSFs and obtain the main effective PSFs on human fatigue. On the other hand, by reducing the size of input variables, there is no need to spend more time and cost for PSFs data gathering.

3.2 | Accelerated Life Testing (ALT)

All consumers are interested to know the lifetime knowledge of products. Using this knowledge, manufacturers can estimate their cost of production by knowing the failure mode of their machines [33] and [34], and end customers can predict the maintenance cost of their appliances. The lifetime of most machines is long and the manufacturers cannot implement common lifetime experiments to ensure the failure rate of machines. To overcome this issue ALT has been proposed.

ALT identifies the load stress levels of a system (or machines or components) and studies the effects of increasing this stress during the life test [35]. In other words, during the ALT, the machine works with a stress higher than its common levels of loads or different environmental factors in order to accelerate the failure occurrence cycle [36]. ALT reduces the testing time to estimate behavioral characteristics such as failure rate, and lifetime for a machine in normal conditions. In ALT, all stress levels are not examined, and the test is conducted in some stress levels, and extrapolation is used to estimate the life distribution at the desired conditions. Since extrapolation methods have statistical errors, several ALT have been proposed by researchers to eliminate the extrapolation errors.

To use ALT, the failure distribution should be identified, and the AF should be defined to propose the ALT distribution function [36]. Three well-known distributions in ALT are Weibull, Exponential, and Log-normal distribution [37]. Weibull is most used among these three distributions [38].

The acceleration relationship selection is important in ALT; this relationship is selected according to the types and numbers of AF. For example, if the temperature is considered as AF, the Arrhenius is an appropriate relation. Eyring Inverse Power Law (IPL), Temperature-Humidity, Temperature Non-Thermal Relationship are the most used relation in ALT.

In this paper, we consider the Performance Shaping Factors (PSFs) as AF, and select the proper acceleration relationship according to the number of effective PSFs obtained by PCA methods. In fact, we aim to propose a quantitative method for human fatigue and reliability calculation instead of common qualitative human fatigue measurement methods.

3.3 | Human Fatigue

Fatigue refers to the issues that arise from excessive working time, poorly designed shift patterns, inappropriate tools, and poor ergonomics. Fatigue is usually considered to be a decrease in mental or physical performance of human that results from long exertion, sleep loss, or disruption of the body's internal clock. It is also related to workload, in that workers are more easily fatigued if their work is machine-paced, complex or monotonous. Fatigue leads to a reduction in human's workforce and consequently to increase the Human Error Probability (HEP).

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The physical fatigue involvement in HEP has been investigated by some researchers. Studies on muscle fatigue have been going on since the late 1800s [39] and [40], and research has mainly focused on the fatigue rate in terms. Xia and Law [41] presented a three-state model to assess human fatigue. Myszewski [42] proposed a curve-based model on error rate to show that human error increases as fatigue increases over time. Michalos et al. [43] proposed a scoring method for physical fatigue using the fatigue model of [16]. They also provided a method to calculate the corresponding error rate based on the work of [9]. Jamshidi and Seyyed Esfahani [44] proposed a model to assess the fatigue of human resources in production systems. Since fatigue is a wide-ranging term, it cannot be directly evaluated. Fatigue must be inferred from its related factors, such as excessive sleepiness, reduced physical and failure rate of human resources [45]. For physical fatigue, fatigue can be measured using physical factors such as heart rate [46] and force. One of the most popular fatigue relations has been proposed by [47]. He proposed that fatigue value can be calculated using *Eq. (2)*.

$$f(t) = 1 - e^{-\lambda_f . t}. \tag{2}$$

Where f(t) is the fatigue accumulated by time t, λf is the human fatigue rate. The fatigue rate represents the rate at which the fatigue occurs.

The failure rate is affected by many factors such as human skill, training, work type, equipment, and environmental condition such as temperature, light, vibration, etc. therefore, we can assign a unique failure rate to a human in a specific job implementation. Finding the human fatigue rate in each environment requires several experiment implementations with different conditions. These different conditions have been known as PSFs. In this paper, we study the historical data on human failure and select the most effective PSFs on human fatigue by PCA method; then the most effective PSFs are considered as AF to propose the accelerated fatigue relation that considered the environmental conditions in production systems. The accelerated fatigue relation will be presented in the next section.

3.4 | PSFs Selection by PCA

PSFs can enhance or degrade human performance and provide a basis for considering potential influences on human performance and considering them in the quantification of HEP. There are several categories of PSFs such as direct/ indirect, internal/external, etc. The most popular PSFs are shown in *Table 1*.

Table 1. Most popular PSFs.

No.	PSF Title	No.	PSF Title
1	Training & Experience	9	Equipment Accessibility
2	Available Time	10	Fitness for Duty
3	Team/Crew Dynamics	11	Instrument Availability
4	Environment	12	Workload/Stress
5	Communications	13	Ergonomics/HIS
6	Communications	14	Need for Special Tools
7	Complexity	15	Realistic Accidents
8	Available Staffing		

Considering the PSFs proposed in *Table 1*, it's hard to analyze all the 15 numbers of PSFs in manufacturing systems, to overcome this issue, researchers tried to reduce the effective PSFs. Boring studied the important PSFs and proposed eight PSFs that are considered as the most effective PSFs in HRA methods [22] Available Time, Stress, Complexity, Experience and Training, Procedures, Ergonomics, Fitness for Duty, Work Process are the eight effective PSFs. Each PSF has a predefined level and each level has a specific value [48] and [49]. For example, the values of stress are shown in *Table 2*.

Table 2. The value of PSF level (Stress).

PSF level (Stress)	Multipliers Action	Multipliers Diagnosis
Extreme	5	5
High	2	2
Nominal	1	1
Insufficient information	nominal	nominal
Highly complex	5	5
Moderately complex	2	2

The multiplier values were attributed by analysts on the basis of several studies. These multipliers should be standardized, if we face an abnormal manufacturing system. In this paper, we consider these 8 PSFs and investigate the human fatigue, regarding these PSFs value and then extract the most effective PSFs using PCA. In order to find the effective PSFs, we investigated 15 historical data for a lathing workshop that presented in *Table 3*, the time for fatigue measurement is equal to 1 hour, each time unit are considered to be 1 hour.

Table 3. The PSFs value for each instance.

	PSFs	Available Time	Stress	Complexity	Experience And Training	Procedures	Ergonomics	Fitness For Duty	Work Process	Fatigue
Instance NO.	Ins 1	0.1	2	5	3	20	0.5	5	0.5	0.130
	Ins2	10	2	2	0.5	1	10	1	0.5	0.110
	Ins 3	10	1	2	1	50	1	5	5	0.126
	Ins 4	0.1	1	1	1	5	0.5	1	0.5	0.035
	Ins 5	10	2	5	3	50	1	5	5	0.165
	Ins 6	0.1	2	5	0.5	1	1	5	1	0.078
	Ins 7	0.01	1	1	0.5	1	1	1	5	0.027
	Ins 8	0.01	5	2	1	1	1	1	5	0.086
	Ins 9	0.01	5	2	0.5	1	10	5	5	0.138
	Ins 10	10	2	1	3	1	10	5	5	0.150
	Ins 11	1	1	5	0.5	1	10	1	5	0.094
	Ins 12	0.1	5	5	3	50	10	1	1	0.157
	Ins 13	0.01	5	5	0.5	20	10	5	0.5	0.142
	Ins 14	0.1	5	2	3	5	0.5	5	1	0.126
	Ins 15	0.1	5	2	3	5	0.5	5	1	0.134

To reduce the number of PSFs to make the data easier to analyze, the PCA method will be implemented. The results of PCA method are shown in *Table 4*.

Table 4. Eigen analysis of the Correlation Matrix.

Eigenvalue	2.7430	1.7996	1.3479	1.1389	0.7193	0.6709	0.3977	0.1681	0.0145
Proportion	0.305	0.200	0.150	0.127	0.080	0.075	0.044	0.019	0.002
Cumulative	0.305	0.505	0.655	0.781	0.861	0.936	0.980	0.998	1.000

The first three PSFs (available time, stress, and complexity) explain 65.5% of the variation in the data of *Table 3*. Therefore, these three PSFs can be used to analyze the fatigue value. The impact of each PSF is shown in *Fig 1*.

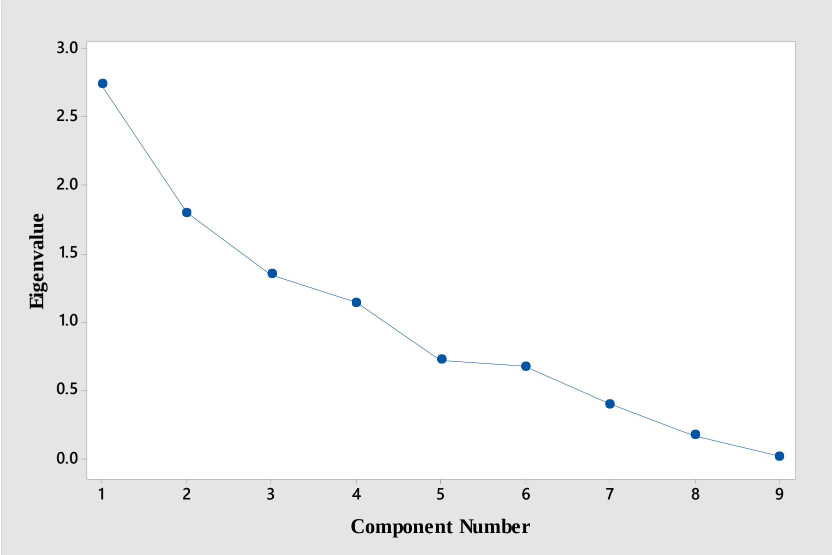

Fig. 1. The eigenvalue for each PSF.

On the other hand, the third PSF (complexity) has a positive correlation with the second PSF (stress), and we can find if the work complexity increases, then the worker stress also increases. Regarding this issue, we select the Available Time and stress as the two effective PSFs on human fatigue. The proposed data in *Table 5* also confirmed these results. As it could be seen, the available time and stress have the most correlation with fatigue. The fatigue correlation value with available time and stress is 0.276 and 0.313, respectively. *Fig. 2.*shows the correlation of these 8 PSFs with the most effective PSFs.

Table 5. Eigenvectors for each PSF.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
Available Time	0.165	-0.641	-0.043	-0.090	0.214	-0.342	0.197	-0.523	0.276
Stress	0.244	0.489	-0.163	-0.421	0.042	0.370	0.365	-0.358	0.313
Complexity	0.298	0.180	-0.219	0.651	-0.339	0.024	-0.315	-0.403	0.173
Experience And Training	0.421	0.041	0.362	-0.143	0.462	0.100	-0.610	0.103	0.251
Procedures	0.402	-0.234	0.064	0.439	0.165	0.362	0.497	0.411	0.115
Ergonomics	0.084	-0.023	-0.809	-0.123	0.126	-0.209	-0.156	0.411	0.265
Fitness For Duty	0.383	-0.001	0.279	-0.260	-0.653	-0.370	0.083	0.279	0.245
Work Process	-0.076	-0.509	-0.125	-0.252	-0.393	0.650	-0.279	-0.017	0.041
Fatigue	0.571	-0.048	-0.200	-0.178	0.008	-0.035	-0.019	-0.100	-0.767

Fig. 2. The relation between PSFs.

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3.5 | Acceleration Human Fatigue Test (AHFT)

The ALT methods have been proposed for one or more AF to estimate the reliability and fatigue. In most practical applications, fatigue is a function of more than one variable (stress types). In these cases, the General Log-Linear (GLL) can be used. GLL describes a life characteristic as a function of a vector of variables such as X=(X1,X2,...Xn), the GLL relation is as follows:

$$L(x)=e^{\alpha_0+\sum_{j=1}^{n}\alpha_j X_j}. \quad (3)$$

Where α0 and αj are the relation parameters that should be estimated and X is the AF vectors. This relationship can be further modified through the use of transformations and can be reduced to other ALT methods such as Arrhenius and IPL. Regarding this fact, we can use IPL method instead of GLL by using an appropriate transformation. To implement the ALT for human fatigue we use the GLL method with some transformation and consider the available time and stress as the AFs. Since we have 2 AFs we should estimate the α0, α1, α2 as the GLL parameters so we can predict the fatigue value according to stress and available time for the future dataset. The results of GLL implementation have been shown in *Table 6*, the confidence level is equal to 99%.

Table 6. Regression table.

Predictor	Coef	Standard Error	Z	P	Lower 99.0% Normal CI	Upper 99.0% Normal CI
Intercept	36.60	15.72	2.33	0.02	(3.90)	77.09
Available time	0.05	0.02	2.38	0.02	(0.00)	0.09
Stress	(10,723.90)	4,344.03	(2.47)	0.01	(21,913.40)	465.56
Shape	3.64	0.86			1.97	6.71

Regarding the result presented in *Table 6*, we can estimate the fatigue of human resources with different available times and stress levels. For example, the estimate of fatigue for available time= 0.1 and stress= 5 is shown in *Table 7*.

Table 7. The estimation of fatigue with PSFs value.

Available time	Stress	Percentile	Standard Error	Lower 99.0% Normal CI	Upper 99.0% Normal CI
0.1	5	0.114565	0.0200486	0.0729939	0.179811

The percentile value shows the fatigue of human with the mentioned specifications. The effect of stress and available time on fatigue, are shown in *Figs. 3-4*. It could be seen, that fatigue increases when stress is increasing and available time is decreasing.

To verify the accuracy of the proposed model, five instances have been investigated, and the relative error has been calculated for each instance. The provided results shown in *Table 8* indicated the proposed model could estimate human fatigue with an acceptable error range. In other words, reducing the time and cost by using the PCA and ALT did not cause a significant error.

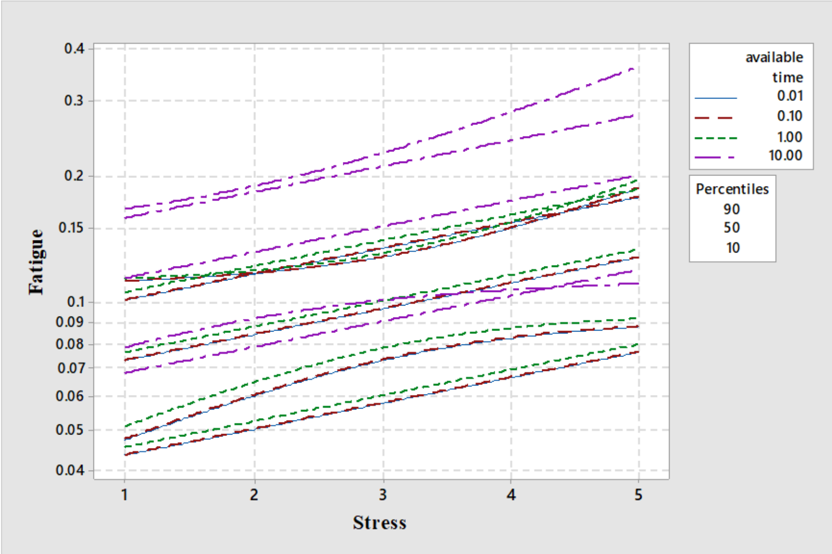

Fig. 3. The relation between fatigue and stress in different stress value.

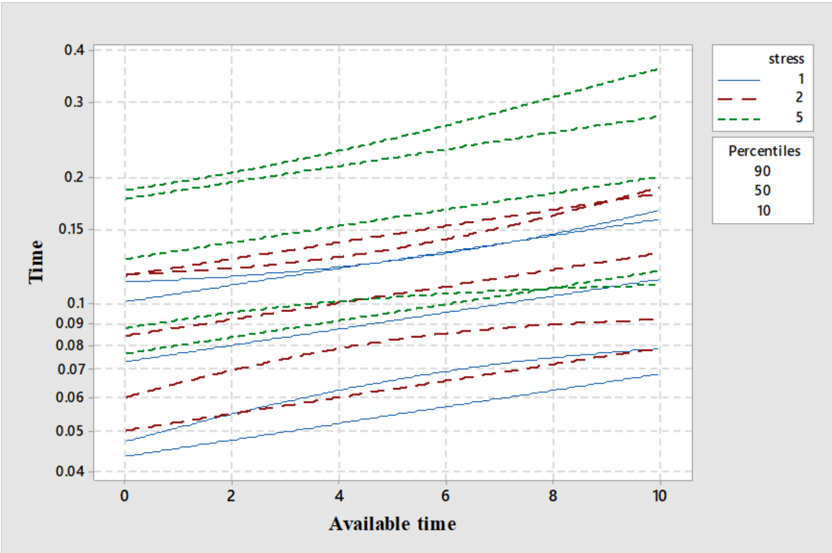

Fig. 4. The relation between fatigue and available time in different time value.

Table 8. The relative fatigue error.

	Available Time	Stress	Complexity	Experience And Training	Procedures	Ergonomics	Fitness For Duty	Work Process	Fatigue	ALT- Fatigue	Relative Error
Ins 1	10	5	5	0.5	20	10	5	1	0.195	0.216	0.1060
Ins2	1	5	2	0.5	50	0.5	1	5	0.062	0.069	0.1150
Ins 3	1	5	1	0.5	50	10	1	1	0.073	0.080	0.0980
Ins 4	10	5	1	1	5	1	5	5	0.162	0.175	0.0830
Ins 5	0.01	5	2	1	1	10	5	1	0.114	0.130	0.1380

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4 | Conclusion and Future Work

In every manufacturing systems, human has the most impact on quality and safety, regardless of the role of human, every plan such as production scheduling, quality improvement, and cost reduction are doomed to failure. Many methods have been proposed to quantify the human effects in manufacturing systems. Most of these methods require a lot of data collection and several experiments. Considering this fact, in this paper, we tried to propose a simple method for human resource fatigue calculation. In this paper, we used the ALT to estimate human fatigue using PSFs. The proposed model can decrease the data gathering time in comparison with common human fatigue models. To reduce the amount of required data for fatigue calculation, the PCA method has been implemented to find the most effective PSFs. The performance of the proposed method was examined for a real case (lathing manufacturing system), and the provided results indicated that the proposed model could obtain an efficient and effective value for human fatigue using fewer data and costs. It's worth mentioning that future researches could consider the potential relation of PSFs and another formulas of ALT. Investigating the effect of another formulas for ALT on human fatigue prediction error, can be an interesting issue for future works.

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E-ISSN: 2717-2937 | P-ISSN: 2783-1337

International Journal of Research in Industrial Engineering

www.riejournal.com

Int. J. Res. Ind. Eng. Vol. 10, No. 4 (2021) 358–370.

Paper Type: Research Paper

Harmonisation of the Engineering Disciplines Enhanced by the Learning Factory

Vusumuzi Malele[1],*, Mhlambululi Mafu[2]

[1] South African Government, Department of Science and Innovation, Tshwane University of Technology, South Africa; vusimalele@gmail.com.

[2] Department of Physics and Astronomy, Botswana International University of Science and Technology, Palapye, Botswana; mafum@biust.ac.bw.

Citation:

Malele, V., & Mafu, M. (2021). Harmonisation of the engineering disciplines enhanced by the learning factory. *International journal of research in industrial engineering, 10* (4), 358-370.

Received: 16/09/2021 Reviewed: 14/10/2021 Revised: 09/11/2021 Accepted: 17/12/2021

Abstract

All engineering graduates must possess specific essential competencies when leaving universities to transition to the industry or be successful in the world of work. This paper adopts a literature review approach to synthesise available secondary data regarding creating harmony among engineering disciplines. It uses the illustration of a vending machine to indicate how various engineering disciplines could be harmonised through the Learning Factory platform. Moreover, it provides some ideas for harmonising engineering disciplines. The main findings of this work suggest that the Learning Factory concept is a critical ideology that is worth implementing, especially by developing. The Learning Factory environment can produce well-rounded graduates capable of applying technical and non-technical skills to solve community challenges, including being entrepreneurial and innovative to drive economic growth and development. The paper concludes by providing insights demonstrating that the concept of a Learning Factory can also be utilized for addressing other engineering and industrial-related challenges.

Keywords: Harmonisation of engineering disciplines, Learning factory, Vending machine, Industry–ready graduates, Knowledge transfer, Problem-solving, Engineering education.

1 | Introduction

Traditionally, engineers are perceived as problem solvers (i.e., people trained to apply the knowledge of mathematics and science to solve problems) [1] and [2]. Engineers could apply their problem-solving, investigation, analytical skills and methods for the provision of clean water, improved farming techniques and automated intelligent systems which result in improved production of goods and services, innovation of better and cheaper building materials which could help provide shelter for people and also increase ease of building houses, thus afford a better standard of living for communities. Therefore, applying relevant engineering and scientific skills, can potentially solve long-standing community challenges, thus warding off poverty and increasing economic growth and development. On the bigger picture, communities are part of a country, so an increase in their economic growth ideally leads to an overall increase in the overall country's economic growth. Subsequently, this will assist countries under study by closing the unemployment gap, increasing economic growth and development, and allowing developing countries to catch up with others.

Corresponding Author: vusimalele@gmail.com

http://dx.doi.org/10.22105/riej.2021.314637.1265

When a community's problems are solved, in general, their standard of living improves and thus reduces poverty [3] and [4]. In the bigger picture, efforts to ease poverty in a community implicitly lead to economic growth, aiding communities to catch up with others. In order for engineering to achieve the goals of assisting countries to catch up, the different engineering disciplines must come into harmony [5]. In this paper, a Learning Factory (LF) concept is presented as a strategic tool in an industry-simulated environment where students and academics could experience the benefits of harmonisation of engineering disciplines. An industry-simulated environment is an environment that allows the integration of different engineering disciplines to work alongside other technical and non-technical disciplines, such as leadership and management [6]. In this regard, the LF concept would be discussed as a strategy that could foster the harmonisation of the engineering disciplines.

Apart from this introductory statement, this paper is organised as follows: Section 2 highlights the employed research methodology, while Section 3 explores the need to harmonize engineering disciplines. Section 4 discusses the LF conceptual framework. Notably, we describe the LF concept, demonstrate how it can be applied in an educational setting, and illustrate the harmonization of different engineering disciplines and the LF concept using a vending machine. Moreover, we provide a brief history of the LF and its existence in South Africa and Botswana. In Section 5, we discuss challenges and provide some recommendations. Finally, section 6 provides a conclusion to this paper.

2 | Method

This paper adopts a qualitative research approach through a relevant literature review to synthesise available secondary data regarding the concept of creating harmony among different engineering disciplines for economic growth. It uses a vending machine to illustrate how engineering disciplines could be harmonised and what students could learn if this harmony could occur in the LF.

Using a qualitative approach emanates from the purpose and concept underlying this research, i.e., the importance of harmonizing different engineering disciplines and the LF model in the context of catch-up effect and global value chains. Moreover, this research is concerned with the subjective assessment of attitudes, opinions, and behaviour. Therefore, a qualitative study will afford the investigation of the primarily disconnected nature of knowledge interactions, i.e., harmonization of different engineering disciplines, catch-up effect, global value-chains [7].

Using various search terms and keywords related to harmonizing engineering disciplines and learning factories at universities, we conducted searches and collected related full-text manuscripts. This was followed by developing inclusion and exclusion criteria to identify relevant citations and identified information applicable to our research objectives. Subsequently, we reviewed studies on the harmonization of engineering disciplines and the LF. Thus, these research approaches will improve understanding of all these phenomena and probe new perspectives.

3 | Harmonisation of Engineering Disciplines

Over recent years, various works on the harmonisation of engineering disciplines have been undertaken. In the context of this work, harmonization of engineering disciplines refers to the process of integrating different engineering disciplines to produce a coordinated and consistent engineering discipline that balances theoretical and practical knowledge to afford students a practical experience and understanding of the full range of issues involved in product design, manufacturing planning, fabrication assembly and testing of functional products [8] and [9]. In a way, the harmony of the engineering disciplines involves engineers from different disciplines (or even within the same discipline) or different countries, or different value chains merging their skills to solve challenging issues, revolutionize industries and create employment. On the other hand, the harmonization concept seeks to determine minimum skills that must be possessed by an engineer so that they can contribute positively to the industry and subsequently grow the economy. Notably, the need to transfer knowledge across different organizations, adapt to different work environments, and assimilate information underlines the need to harmonize the engineering disciplines.

Howard [10] argues that written communication skills are essential for engineers in the workplace yet developing these skills in undergraduate engineering continues to be a significant challenge. In response, Howard [10] proposed that curriculum innovation that integrates written tasks in engineering courses through online writing tools should be provided to students to harmonise engineering disciplines. Accordingly, they proposed creating an integration model based on a risk communication framework in collaboration with leadership, learning support, and academics.

Birch et al. [11] presented a methodology and toolkit for analysing multidisciplinary engineering models to help practitioners maximise the utility of complex models that were extracted, visualised and analysed through interdisciplinary computing and metrics. These methods expose, manage and reduce model complexity and risk while supporting engineers in optimising efforts and providing insight into the multidisciplinary model composition.

On the other hand, Mordinyi et al. [12] point out that harmonising or combining the efforts of various engineering disciplines is essential when engineers are expected to develop and implement large engineering projects. This is because each engineering discipline utilizes specific engineering tools and data model concepts representing interfaces to other disciplines. Therefore, integrating these different engineering disciplines opens more opportunities for innovation and possibly leads to the realisation of novel products which may be commercialised, thus opening up possibilities for creating economic wealth.

Moreover, Craig [13] records that through his 25-years of experience as an engineering educator, researcher, and consultant, two dilemmas faced by companies could be identified as: (i) senior engineers with experience and integrated know-how are retiring and taking with them the core competencies, and the new engineers have no multidisciplinary, integrating, systems experience; and (ii) academia does not teach integrated know-how leading to failure for the engineers to have multidisciplinary harmonised engineering experience. These two lead to the loss of competitive advantage, making companies question how they can effectively and efficiently capture engineering expertise and enhance the engineering workforce to keep on the competitive advantage. As a way forward, these companies decided to send some of their young engineers to study towards a Masters' degree. Unfortunately, they found that most Masters' degrees usually consist of 8-10 courses and an additional short research project with very theoretical and little integration or practical applications. Secondly, the cost and time commitment are very high. Engineers still need to work full-time while having other social responsibilities, for instance, taking care of their families. Consequently, Craig [13] proposed that a solution to these two dilemmas could be a renewed focus on multidisciplinary, model-based systems engineering and a paradigm shift in how education for a practising engineer is delivered.

Due to the growing number of requirements and the introduction of new technologies, current trends indicate that more engineering disciplines are involved in multidisciplinary system design. Zheng et al. [14] studied how to achieve an integrated design for multidisciplinary systems using the knowledge-based engineering approach that focuses on designing and implementing the partial discharge detection system and a belt conveyor system. They found that some of the unnecessary iterations could be resolved by interfacing multidisciplinary disciplines, resulting in a concurrent design process that harmonised different engineering disciplines during the detailed design phase. Thus, this displays the potential of harmonising engineering disciplines in providing solutions to long-standing challenges in work environments. However, in [10]-[14], propositions do not speak to the immediate need of supplying industry with industry-ready graduates who could be trained in an academic-industry simulated environment while still enrolled at university. Therefore, to produce industry-ready graduates who could appreciate the harmonisation of engineering disciplines, students should be trained in an academic-industry simulated environment while continuing with their university curriculum.

4 | Learning Factory

Several definitions of the term "Learning Factory (LF)" have been proposed within the community. According to [15]-[17] a LF refers to a learning environment specified by processes that are authentic, include multiple stations, and comprise technical as well as organizational aspects, a setting that is changeable and resembles a real value chain, a physical product being manufactured, and a didactical concept that comprises formal and non-formal learning, enabled by own actions of the trainees in an on-site learning approach.

The LF was founded on three beliefs: lecturing alone is not sufficient, students benefit from interactive, hands-on experiences and experiential, team-based learning involving student, faculty and industrial participation enriches the educational process and provides tangible benefits to all [18] and [19]. These collaborations and experiences provide students with vast opportunities and preparedness to tackle real-world challenges and provide better insights into their solutions [20]. Besides the hands-on experience on different industrial models, methods and processes after comprehending theoretical concepts in the classroom, students access state-of-the-art machinery and equipment and processes to input new ideas [21]. For instance, through university-industry collaboration, the industry can provide facilities for students to conduct their project work. Thus, it provides a conducive learning environment where processes and technologies are based on an accurate industrial site, allowing a direct approach to the product creation process. They are, in fact, based on a didactical concept featuring experimental and problem-based learning [22].

On the other hand, these collaborations allow industries to remain at the forefront of technology through research that university students and researchers undertake. Through research, it became eminent that experiential learning has more significant benefits than the usual traditional teaching method without showing or practically guiding them [23]. The latter teaching and learning approach could easily be facilitated by an academic-industry simulated environment that may replicate a factory where students practically assimilate real-world processes and activities. This academic-industry simulated environment is known as the LF. Besides the type or purpose of the LF, learning broadly takes place through teaching, training and research.

The LF concept promotes the ideology in which engineering disciplines work alongside other technical and non-technical disciplines [6], [24], [25]. It integrates different teaching methods to move the teaching-learning processes closer to real industrial problems [24]. According to [26], the main goals of the LF are either technological and organizational innovation (if used for research) or an effective competency development (if used for education and training), i.e., the development of participants' ability (including motivational and emotional aspects) to master complex, unfamiliar situations. Moreover, the [27] argues that the objective of an LF is to integrate a practice-based engineering curriculum that balances analytical and theoretical knowledge with physical facilities for product realization in an industrial-like setting. Therefore, the LF model emphasizes practical experience; therefore, Engineering Technology (ET) and other programs that emphasize hands-on experiences for students are well suited to implementing the LF model. Therefore, to achieve such goals, the LF standard structure comprises six dimensions and corresponding features, and these are illustrated in *Fig.1*. These dimensions consist of purpose, process, setting, product, didactics and operating model.

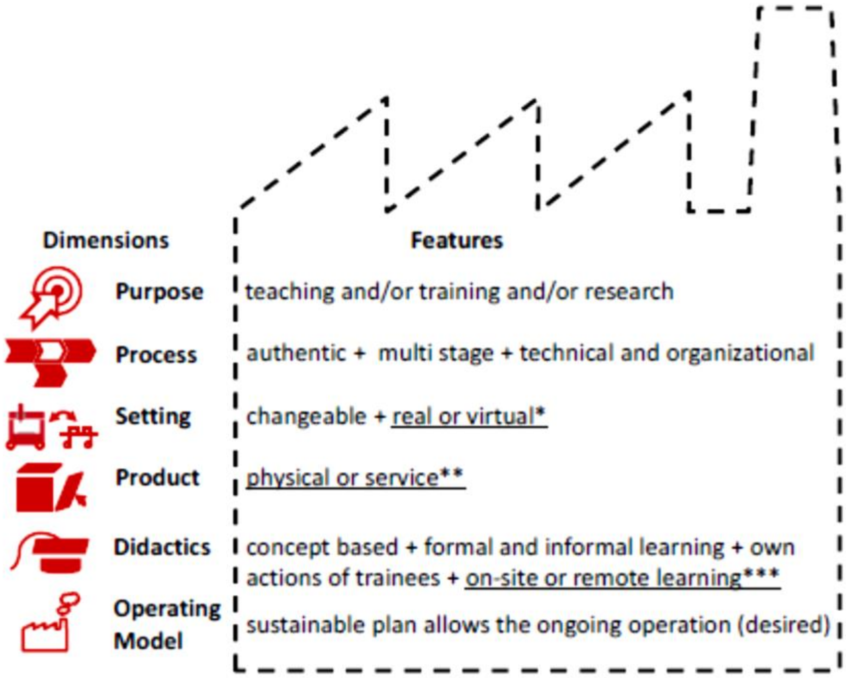

Fig. 1. The six dimensions of the LF [26].

While the LF concept can be implemented in various ways; however, in the broadest sense, it is further away from reality and less hands-on though it offers advantages regarding the scalability, location of independent use, or a widened scope of addressed problems. These are modified in at least one of the following directions: (a) virtual representations of valu-added chains; (b) connection of trainees to the learning processes based on remote information and communication technology connections, and (c) product which comes in the form of a service. In the narrow sense, the LF provides an entire value chain for a physical product in which participants can perform, evaluate, and reflect on their actions in an on-site learning approach [26] and [27]. The LF covers various learning environments that provide a reality-conformed production environment where only minor abstractions are possible concerning the industry [23], [26], [28]. For example, [26] highlights and discusses six varieties of LFs scenarios to show that no LF usually resembles another or is used in the same way. The LF supports the idea that its concept could be applied in the education sector to create an environment where students would be oriented towards workplace problems [29] and [30]. This is illustrated by *Fig. 2*, which demonstrates the LF bridging the gap between students' laboratory experiments and industry work.

The authors [30] explain that in an LF environment, students attempt to solve a real-world problem using a systematic, integrative approach by applying various concepts they would have learned in their LF tailor-made modules. The problems could be holistic and complex, not unidirectional, thus affording students various options as solutions, necessitating the need to integrate different engineering concepts and develop a tailored solution that addresses the challenges at hand [31]. Moreover, in the LF, students perform some tasks that assist them in their future career paths and develop personal skills for building strong confidence in their future workplace. In this regard, the LF model pursues an action-oriented approach, with participants acquiring competencies through structured self-learning processes in a production-technological learning environment.

The LF has been used for educational purposes, research and training in areas such as manufacturing, energy efficiency, service operations and processes [32] and [33]. For example, [33] conducted a critical analysis of the plant processes to obtain all the required parameters to set up a simulated model of a

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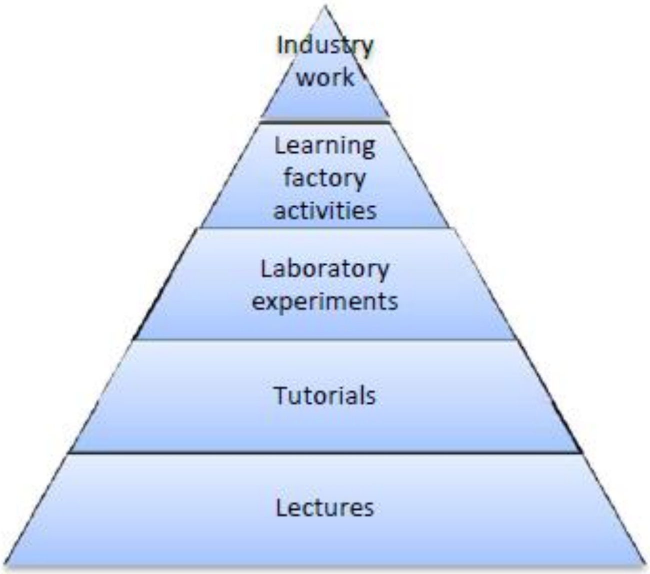

Fig. 2. The LF gap filling [29].

PLC controlled simulation for a coupled tank system based on an existing dual-tank educational process control plant. The authors argue that this kind of simulated platform uses existing standard industrial software and hardware that gives engineering students the necessary exposure to transition to the industry successfully. Also, it enhances learning capability because what is taught is no longer limited to only physically available equipment. Furthermore, such a platform solves other problems commonly faced in learning environments, such as limited resources and space constraints, by opening up the possibility of remote laboratories.

As a result, this demonstrates that the LF has a great potential of facilitating new learning approaches that allow training in a realistic manufacturing environment, modernize the learning process and bring it closer to the industrial practice, leverage industrial practice through the adoption of new manufacturing knowledge and technology, and boost innovation in manufacturing by improving work processes [26] and [33]. Furthermore, the LF promotes the capabilities that drive manufacturing competitiveness among young engineers [26]. These capabilities could include problem-solving capability, systems thinking capability, talent or creativity-based innovation. Moreover, LFs could enhance engineer outputs and orientation, gear them towards excelling in their studies and align them with their rightful engineering skills, including developing them into entrepreneurs and innovators. In this regard, it further proves that the LF is a critical strategic tool that universities and industries can use to harmonize engineering disciplines.

The design and physical building of LF could come with many challenges. However, the LF should be designed to achieve multiple objectives such as ease of roaming, display area, and special display areas [34]. Literature provides a guideline regarding ready-made designs. However, it might be difficult for a design student or graduate tasked to design the LF to choose a perfect design. Therefore, authors in [34] suggest the Analytical Hierarchy Process (AHP) as a suitable technique for comparing existing designs for the student or graduate designer to achieve and reach a decision of the final layout design selection.

5 | Discussion

5.1 | The LF in South Africa and Botswana

The literature points that the LF concept was initially coined in 1994 when the National Science Foundation (NSF) in the United States of America (USA) awarded a consortium led by Penn State University a grant to develop a “learning factory”. In that regard, the Bernard M. Gordon LF was established as a state-of-the-art facility with a mission to help bring the real world into the classroom by providing engineering students with practical hands-on experience with industry-sponsored and client-based capstone design projects. The Bernard M. Gordon LF is illustrated in *Fig. 3*.

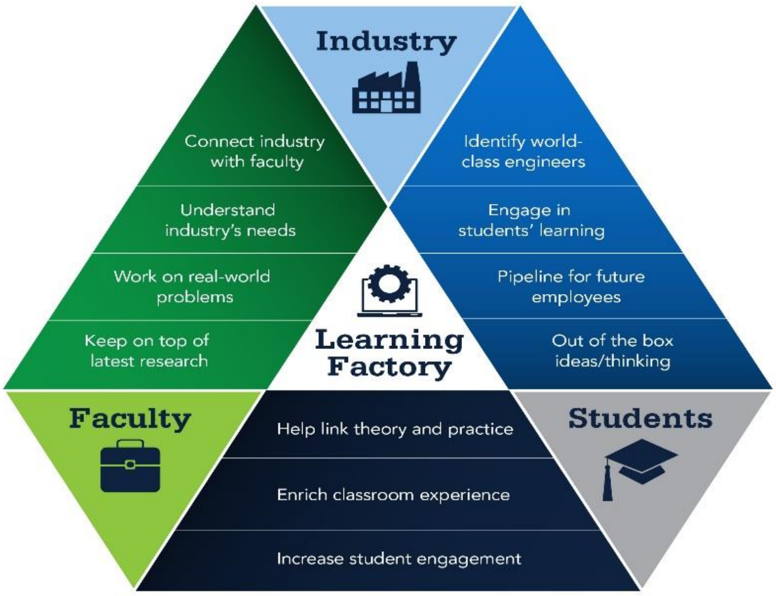

Fig. 3. The Bernard M. Gordon LF model. (Source: http://www.lf.psu.edu).

To use the Bernard M. Gordon LF, a student must be enrolled in an engineering course at the College of Engineering, Penn State University; and work on a course-related project. Due to University regulations, the LF cannot be used for personal work unrelated to a course. It is recorded that since its inception, the Bernard M. Gordon LF has completed more than 1,800 projects for more than 500 different sponsors, and nearly 9,000 engineering students at Penn State University Park participated in such a project. Since its inception, the use of LFs has increased widely, particularly in the USA and Europe, and has taken many forms of facilities varying in size and sophistication to enhance the learning experience of trainees in one or more areas of knowledge [26]. In South Africa, there is an indication of LF environments at Stellenbosch University (SU), Nelson Mandela University (NMU) and companies such as Nissan South Africa.

The Stellenbosch University Learning Factory (SULF) provides a supplementary educational method to cover the gap between abstract lectures in universities and practical experiences required in the workplace [29]. The SULF projects provide a similar real-life environment for students to gain practical and hands-on experience, which is not included in their current curriculum. It develops operations management methods, such as lean management, process optimization and change management, including soft skills such as communication, teamwork, project management, intercultural and leadership skills [29].

The LF in Logistics Management at NMU assembles different products such as skating boards with computer programmes (http://sms.mandela.ac.za/News/Prof-Horn-Participates-in-the-learning-factory-pro). Accordingly, students have to order all the individual parts, manage the inbound stock, to assemble, and adapt to on-time release on different work stations. Such training provides students with skills such as communication, project management, people management.

The Nissan South Africa, a car manufacturering company, has built a modern new LF centre at its vehicle manufacturing plant in Rosslyn, Gauteng Province. Its objective is to make a significant contribution towards assisting Nissan to meet the increasing demands for greater productivity, skills transfer, and global standards of quality by training and developing its employees. The new centre consists of sizeable modern lecture rooms, a computer training facility, and technical training workshops situated close to the plant and catered for the main assembly areas (paint, body and mechanical). It is envisaged that skills developed in the Nissan LF would contribute to meeting the objectives of the company's multiskilling programme and achieving the higher levels of quality required. Unfortunately, this LF is for NISSAN employees, hence not accessible to local universities.

In 2015, Fluor Botswana, a global engineering, procurement and construction company, opened an office in Gaborone, Botswana. The office serves as the company's operations base to expand and diversify business activities across sub-Saharan Africa. Through its international-based LF known as Fluor University, Fluor has implemented an employee development program that provides virtual training to its employees and their stakeholders worldwide. In addition, Fluor University consists of five virtual colleges: (i) construction and fabrication, (ii) project management, (iii) project controls, (iv) supply chain, and (v) engineering. In this setting, trainees have access to more than 200 instructor-led courses in traditional classrooms or through video distance learning. Fluor University is accredited by the International Association for Continuing Education & Training (IACET) to grant Continuing Education Units (CEUs) needed for professional certifications.

Fluor Botswana is also equipped with the required technology to allow individuals to access Fluor University's online, instructor-led and video distance learning. Thus, this indicates the LF environment found in Botswana, which is put in place to empower many Botswana employees (of Fluor and its stakeholders) and contribute to building a sustainable workforce in the country. Unfortunately, there is no indication of a strong relationship between Botswana's two public universities and Fluor University. Such a relationship is critical as it could assist in producing industry-ready graduates. Therefore, unlike in South Africa, where the LF is established within the university settings, an LF environment must be attached to Botswana universities.

5.2 | Illustration of Harmonization of Different Engineering Disciplines and LF Concept by Using a Vending Machine

Engineering brings together significant economic benefits and thrives on teamwork, which could be made possible by communicating ideas and exchanging knowledge. Harmonisation of engineering disciplines is critical as it could be the birthplace of systems and forums that allow engineers to interact and share ideas and knowledge to design and develop a client/user acceptable product or service. An immediate example of how an LF and harmony of engineering disciplines could be realised is by working together to create something novel and acceptable to a client or user can be demonstrated through the design, development and manufacturing of a vending machine system.

Consider an industry that aims to design and produce an intelligent vending machine; therefore, getting a good design and product requires, at the primary level, different mechanical, electrical, industrial and computer engineers, including project officers/managers, business development team and marketing teams.

In particular, to produce a vending machine, the following engineering disciplines could be vital:

The requirement or business analyst or product marketing engineer facilitates meetings with the industry that manufactures vending machines and gathers the necessary client's requirements. This engineer also interacts with potential users or customers to solicit more information, such as the look and feel of the vending machine. In the LF, the engineers mentioned above train students to gather the necessary data and information (through structured or unstructured interviews, questionaries) to manufacture the vending machine system. In addition, students learn various essential manufacturing techniques; for instance, before any system could be manufactured, its manufacturing specification must first be put into place.

By way of an example, the requirements engineer may develop a necessary flowchart that the software or product development engineer could use to design and provide the software code for the vending machine. As an illustration, such an engineer could represent the information for other engineers as follows: (i) the machine should accept coins from R1 to R5 and paper notes from R10 to R200; (ii) allow the user to select products Coke or sweets (iii) allow the user to get a refund or cancel the request if there is a need; (iv) return the selected product and remaining change if any; and (v) go back to the original purchasing stage or allow the reset operation for a vending machine supplier.

Since the latter requirement statement is the essential part of the problem, the requirements engineer assists students to read the problem statement multiple times to get a high-level understanding of the problem. The students should be trained to become aware that if requirements are unclear, they might mislead other manufacturing teams, and the final product might not meet user specifications. As a result, the training in the LF should be cyclic and interactive so that students gain a clear understanding of the client and user specifications.

A software or product development engineer needs to use object-oriented software languages (such as Java) to design, code and test the vending machine. Also, this engineer should produce design documents, working program code, and unit test results with this task. Hence, the latter tasks need the software or product development engineer to work alongside the business analysts or project engineers.

In the LF, the engineers, as mentioned earlier, train students to apply techniques of object-oriented language such as encapsulation, polymorphism or inheritance, and how to use an abstract class and interface while solving a problem or designing an application.

The role of mechanical engineers is to design the structure, motor and pump systems of the vending machine to keep the food fresh and drinks cold and deliver the product (food or drink) to the customer when a purchase is made. Some of these tasks might require the expertise of a structural engineer and a refrigeration engineer. For example, when a product is selected (i.e., a user interface designed by a software developer), a screw-shaped wire turns a coil forcing the item off its shelf and into the delivery shoot while avoiding too much pressure on the item else it would be damaged and too little pressure as it would get stuck.

In the LF, the mechanical engineer teaches students structural design techniques and dynamics of the cooling system, stress and strain through the necessary coil dynamics.

An electrical engineer designs and develops electrical regulators to keep food fresh and drinks cold and deliver a selected item. They achieve this by designing microcontrollers that run and monitor various vending machine systems. When a selection is made, the microcontroller sends a signal to a motor designed by the mechanical engineer, which enables payment and delivers the product (food or drink).

The microcontrollers monitor cooling systems, which keep the food fresh and drink cold. Too little power could mean jammed soft drinks and melted ice cream, but too much power could mean excessive electrical heat or burned-out circuitry. In the LF, students learn how to design and use electrical regulators and microcontrollers to facilitate a stable temperature within the vending machine and deliver the right product without losing its freshness.

An industrial engineer designs and develops the machine for accessibility, ease of use, and attractiveness and ensures all the necessary equipment or infrastructure is available. If some equipment is not available, the engineer will purchase it from other equipment providers or is designed or innovated from scratch. The industrial engineer decides on which part of the machine should be placed and how it should be oriented to achieve its goal in the design. They ask themselves questions like, what if a disabled person uses the machine, what if a child is making a purchase, is it intuitive to have the payment slot here or there.

In the LF, students learn from industrial engineers how to design and manufacture a sound system for a client and the user through agreeable satisfaction. The student will also learn how a logistic and supply chain or innovation process works. The student could learn how to create a software system that makes

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it easy for navigation when a selection is made, a secure method of money transfers and communication of the machine's status to the vending company at any time. Furthermore, in the LF, students could learn from the industrial engineers how to reduce waste on the design and development of the vending machine using 5S (i.e. a systematic approach that helps to organize a workplace for increasing efficiency and safety while reducing waste) and shadow boarding approach [35]. The latter could aid students to have a workshop/workstation tools organization technique. Finally, business developers, marketers and entrepreneurs could teach students how to use business processes to profit through the vending machine and its products.

Another example that could illustrate the harmonisation of engineering disciplines and be utilised in the LF to train students is a project that examines the strength of new material. Suppose the strength of new material is determined by a materials science engineer, skills for calculating the tensile and compressive forces that it experiences, and its resistance under these forces are derived from mechanical engineering. Determining the resistance of steel reinforcement inside a concrete block by a civil engineer again calls for skills from mechanical engineering. If this project is conducted in the LF, students will gain the same skills needed to fulfill the project goals.

It is generally a good practice to have engineers from different disciplines who possess core skills in the business of other disciplines to build a more robust human resource. This is beneficial because when presented with a problem, each engineer will contribute to the attainment of a solution. These engineers will also voice their shortcomings, where other engineers could meet those shortcomings by using knowledge from their discipline. The same approach could invite interested engineers to chip in on a project proposed by an engineer from a different discipline who needs other engineers' skills.

In the LF, good practice also increases the multi-criteria group decision-making problem. The latter could be achieved by utilising the Hypersoft set and Fuzzy Hypersoft Set (FHSS) [36], as it will deal with complex parametric data and vague concepts that could be contributed by participating engineers and students. The work by [36] illustrates how FHSS theory plays a role in solving real decision-making problems.

6 | Challenges and Recommendations

While the LF plays a pivotal role in enhancing university-industry collaborations, multi-disciplinary cooperation is not easy to achieve due to each collaborating organisation's inherent challenges. For instance, the current financial infrastructure and funding model at various institutions may render it difficult to allocate budgets for students to spend time in the industry. In addition, project-based learning is usually demanding by nature, particularly the interdisciplinary projects demand on researcher's time and other resources.

Moreover, the collaborating parties need to be realistic in selecting projects that they can work on together. Some projects may be exciting, but the teams must ensure that they have the necessary skills and expertise to undertake them within reasonable timelines. Based on the above initiatives, it can be argued that the LF is a paradigm shift to a university-industry partnership providing real-world problem-solving in engineering education. Therefore, we provide the following recommendations and outline the immediate benefits.

- *The industry as a partner: Industry should be involved at all educational stages (curriculum design, advisory board, project sponsorship, faculty experiences and financial support). Moreover, this will allow universities to match the degree of industry complexity to the learning objectives.*
- *Active learning: A proper environment will enable students to learn independently. The first-hand experience on real-world problems provides an opportunity to develop own skills and knowledge that are more memorable and transferable than in a lecture.*
- *Appropriate facilities to stimulate learning: The learning facilities must guarantee safety, be well-equipped, multidisciplinary (i.e., all students must have access regardless of their specializations) and be visually impressive.*

– *Formal educational training: In addition to their in-depth technical expertise, the engineering teaching staff must possess formal training in education. This will stimulate continuous and methodical improvements based on established and the latest educational principles and practices.*

7 | Conclusion

Africa is endowed with an abundance of natural resources. Instead of African countries benefitting from these resources, they are experiencing a resource curse, i.e., countries rich in natural raw material generally fail to realize rapid economic growth rates. The resource curse suggests that an abundance of raw materials can cause overvalued exchange rates, thus making exports less competitive, crowding out of other sectors of the economy leading to unbalanced growth and resources owned by foreign multinationals, with little of the wealth 'trickling down to ordinary people. Industries based on these abundant natural resources could be developed to solve problems affecting the populations of developing countries. To alleviate poverty, they must sponsor young engineers' creative innovation and help boost the economies of countries they lie in and surrounding areas.

High technology companies can employ about 21 000 people or even more, like the 44 000 people who work for Rolls Royce and its programs, approximately 2% of Botswana's population. Simple efforts such as developing systems that enable fluid networking between innovative youth, potential sponsors and participants in proposed projects could be a good step. Exposure to different technologies is critical in accelerating innovation. If young scientists and engineers are introduced early to the latest technological and scientific developments, they may get acquainted with different technologies and, in some instances, even offer ways of improving them. In fact, this may result in a catch-up effect where developing countries or companies skip other levels of investment.

The key message communicated by this work is that engineers and other individuals should change their way of thinking and adopt ways to understand how other people's ideas work and see where they could fit in to complement their efforts or seek to improve them, resulting in the catch-up effect. Instead of replicating such efforts, looking first to being employed, or even refusing to help with crucial knowledge or other elements, other engineers' projects and ideas would succeed. Based on the illustration of a vending machine, it can be observed that technology in any of the engineering fields can never exist in isolation from other disciplines. This is because the skills involved in any technology are generally interdisciplinary. In that regard, it is suggested that the LF strategy or concept is one of the ideologies that could be implemented by most African universities in partnership with industry and government. The LF provides a paradigm shift to industry-partnered, interdisciplinary, real-world problem-solving in engineering education. The LF environment has a great potential to produce well-rounded graduates who can use technical and non-technical skills to solve African problems and be entrepreneurial and innovative to foster economic growth.

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