A Generalized Model for Automation Cost Estimating Systems (ACES) for Sustainable Manufacturing

O.M. Ikumapayi1*, E. T. Akinlabi1,2*, P. Onu3, S.A. Akinlabi4 and M.C Agarana5

1Department of Mechanical Engineering Science, Auckland park Kingsway Campus, University of Johannesburg, South Africa  
2Department of Mechanical Engineering, Covenant University, Ota, Nigeria  
3Department of Quality and Operation Management, Doornontein Campus, University of Johannesburg, South Africa  
4Department of Mechanical and Industrial Engineering, Doornfotein Campus, University of Johannesburg, South Africa  
5Department of Mathematics, Covenant University, Ota, Nigeria  

*Corresponding author: esther.akinlabi@covenantuniversity.edu.ng, oikumapayi@uj.ac.za

Abstract – Automation technology is a new area of technology that requires proper selection of variables to minimize cost and maximize profit. This paper is aim at developing a mathematical model that will be able to solve all automation cost estimating systems (ACES), be it full automation, partial automation, manufacturing automation or service automation as well as fixed, flexible or programmable automation. Extensive research has gone into cost modeling over the years and many commercial, as well as free software solutions, have been widely exploited to proffer solutions to cost modeling especially in ACES. Hence, a lasting solution to the problem of ACES, its implementation, and application in automated manufacturing and process industries is demonstrated in this paper.

Keywords: Automation, Cost, Estimating System, Mathematical Model, Manufacturing

1. Introduction:
Automation has a fundamental influence on the global economy and will continue to find relevance in centuries to come. In modern manufacturing systems especially in automation systems, high product quality, manufacturing flexibility, and low production cost are essential keys to competitiveness [1]. For this reason, ACES is always an item of primary concern. Today many companies, all over the world, have given up utilizing product produced traditionally in order to avoid failure in the products, declining market share, and loss of profit and sales. As a result of rapid development in automation technology, the delivery period by various companies across all industries to their end users is swift and timely with low price and superior quality [2 – 4]. It is essential to note that companies are still struggling for competitiveness more than the pass in order to remain relevant and profitable [5 – 7]. Generally, the designer has little access to cost information and therefore have limited control over the product cost, although their decisions have impact effects on the cost of a product. This is partly because the amount of cost information is insufficient and the format is unstable [8 – 10]. Therefore, designers need a cost estimation tool to overcome the above limitation. It has been established that the most fundamental ingredient in ACES is the construction of cost models that will give a significant cost estimate based on the collected data. Cost is the most fundamental key point in taking a decision that will influence the selection of manufacturing process [11]. It is essential for automation manager to act earlier enough in the design phase in order to reduce costs by estimating the costs that will eventually result in profit generation.
especially in design as well as automation manufacturing plan phases which will as same time
takes care of any potential changes that could occur [12 – 13]. Notwithstanding, the automation
manager will be capable of influencing effectively the overall product cost through the changes
in design. Moreover, early capacity planning can be achieved by deriving the time for
processing from the estimated cost [14]. However, there will be issues in utilization if the
decisions are based on inaccurate values. The focus of this research is to ensure that there is a
high level of accuracy when automation cost estimating systems (ACES) applied.
This paper describes the development of an ACES model which provides a highly productive
and flexible approach to user customization regardless of the types of the automation system.
Even though a company has good ACES, there is a frequent need to customize the ACES to the
specific manufacturing or service environment of the company.
Kumar and Bhatia [15] used Artificial Neural Network (ANN) and MATLAB software for
estimating the cost of automation via COCOMO model-based software which was capable of
calculating planned efforts and development time.
Different methods and approaches have been adopted in the recent time by different researchers
[16 – 20] in order to proffer solutions to the cost of manufacturing of goods and services to
increase profit and minimize loss. Also, Buonasera [21]; Favi, Germani, & Mandolini, [22];
Muratori et al., [23]; Orisanmi [24] did wonderful works in the area of cost modeling of
manufacturing systems. Notwithstanding, their efforts only dealt with the manufacturing such
as Job shop, Batch, Mass and Flow line manufacturing. In finding the lasting solutions to the
cost of automation of a system, some other researchers have done tremendous works in the area
of cost of automation [25 – 29]. A model which is capable of estimating the lowest operational
cost of a production process executable in an automated factory is presented in this work.

1.1 Cost Automation Technology

Automation as a new technology is associated with the application of complex, Information
technology, electrochemical, electronic, Mechanical as well as information technology systems
in the functional and control of production operation process. Automation has enormously
reduced the need for mental as well as human requirements in all sectors that automation plays
vital roles.
It is essential to let the supposed users of this new technology aware of the costs associated with
it so that future plan on it can be achieved. It is very vital to let the users of automation
technology know that the highest cost reduction is what is referred to as Savings in Labour
Costs.
Labour Costs is a broad term that encompasses the following costs and is not limited to them.
According to Primrose, et al., [30] they are:
1. Internal costs for customizing purchased system
2. Cost of subcontractor during implementation to avert the loss of products
3. Cost of temporary staff to install and the system
4. Consulting Costs
5. Redundancy Costs
6. Cost of software updates
7. Companywide education of personnel who need to understand the system
8. Staff upgrading costs
9. The management costs of the System
10. Cost of disrupted production during implementation
11. Ongoing Education and training
12. Programmer costs
13. Cost of training and educating the people who will as a matter-of-fact operate the system

The essential condiments of running costs in any manufacturing system include the following among others Primrose, et al., [30]:

1. Operating Costs
2. Consumables
3. Cost of hiring/lease of hardware and software
4. Insurance
5. Turn around maintenance cost of hardware and software

1.2 Reduction in Labour Cost

It has been established that automation technology has the capacity to reduce labour costs in the area of maintenance, design as well as production stages. This capacity also extended to the area of inspection and supervision of manufactured parts or products. This new technology has the potential to produce parts in precise accuracy, supervision as well as inspection costs should be significantly reduced. The following has been identified as savings in labour cost according to Primrose, et al., [30]:

1. Labour costs in prototype production
2. Recruitments and training
3. Labour costs in manufacturing
4. Labour cost in manufacturing design
5. Overtime payments
6. Labour cost due to maintenance
7. Labour costs due to the reduction of fitting and assembly requirement
8. Production control costs
9. Operating costs due to engineering and design
10. Direct production labour cost due to fewer setups
11. Inventory control labour cost due to lower WIP and finished goods inventory
12. Support labour cost due to supervision and inspection
13. Labour costs in materials handling

The aforementioned lists of costs can be grouped into different sections as shown in figure 1:
Figure 1: Cost modelling of ownership for all lifetime costs test assets predicting future strategic investments

2. Model of Low-Cost Automation and Concepts of Production

The flow chart shown in figure 2 represent the low cost of automation in a batch manufacturing system

Figure 2: Graphical Model of Low Cost of Automation (LCA)
2.1 Operation Cycle Time

Cycle Time is overall time taken between which a work-unit starts processing and the next work-unit begins i.e. the time one work unit expends on processing or assembling. This consist of mainly effective operation time for machining, tool handling time per workpiece and work-part handling time.

Mathematically,

\[ C_t = \sum (P_t + H_t + T_{ht}) \]

Where

- \( C_t \) = Cycle time, min/Pc
- \( P_t \) = Processing Operation Time, min/Pc
- \( H_t \) = Handling time for both loading as well as offloading Machine for operation, min/Pc
- \( T_{ht} \) = Tool handling time for changing tools, min/Pc

2.2 Rate of Production

1. Batch Production
   Time taken to process a batch (Q unit) = Setup time + Processing time
   Mathematically,
   \[ B_t = \sum (S_{ut} + Q C_t) \]

   Where,
   - \( B_t \) = Time taken for Batch Processing, min
   - \( S_{ut} \) = Time taken to setup a batch in min
   - \( Q \) = Quantity of the batch, Pc
   - \( C_t \) = Cycle time per work-unit in min/cycle

   Average Production time per work unit
   \[ P_{At} = \frac{B_t}{Q} \]

   Where,
   - \( P_{At} \) = Average Production time per work-unit, min/pc
   - But
   \[ P_t = \frac{1}{P_{At}} \]
   Also,
   \[ P_t = \frac{60}{B_t} \]

   Where,
   - \( P_t \) = Production rate per hour, pc/hr
2. Job Shop Production

For Job Production, \( Q=1 \), therefore equation (ii) becomes

\[
B_t = \sum (S_{ut} + C_t)
\]

vi

3. Mass Production

For high production quantity, \( Q = \text{Very Large} \)

Substituting Equation (iii) into Eqn (ii)

\[
P_{At} = \frac{B_t}{Q} = \frac{\sum (S_{ut} + Q C_t)}{Q}
\]

\[P_{At} = \sum \frac{S_{ut}}{Q} + C_t\]

viia

Since \( Q \) becomes very large, the first term of the right-hand side of equation vii tends to zero

\[
\frac{S_{ut}}{Q} \rightarrow 0
\]

Therefore, Equation viia becomes

\[
P_{At} = C_t
\]

4. Flow Line Production

Cycle time = transfer time + longest processing time

\[
C_t = \sum (T_t + \text{Max} T_o)
\]

viib

Where,

\[
\text{Max} T_o = \text{Maximum Operation Times for all the stations on the line}
\]

\[
T_t = \text{Transfer time}
\]

2.3 Manufacturing Lead Time

Manufacturing lead time (MLT) is the summation of time required to manufacture or produce an item, this commences from the time of order, time to setup, queuing time, running time, moving time, inspection time as well as delivery time. Technically, it is the total time spent in converting raw materials into finished goods. This is also known as throughput time or manufacturing Cycle Time.

Analytically,

\[
\text{MTL} = \text{Process time} + \text{Inspection time} + \text{Move time} + \text{Queue time}
\]

In other words,

\[
\text{MLT} = \text{Delivery time} – \text{wait time}
\]

Mathematically,

\[
MLT_j = \sum_{i=1}^{n_0}(S_{utji} + Q_j C_{tji} + T_{no ji})
\]

viii
Where, 
MLT$_j$ = manufacturing lead time for part or product $j$ in min 
n$_o$ = the number of separate operations through which the work unit must be routed 
$Q_j$ = Quantity of part or product in the batch (pc), $C_{ij}$ 
$T_{no}$ = the non-operation time associated with the same machine or operation. 
$T_{noij}$ = non-operation time associated with operation $i$ and $j$ (min),

In other to simplify and generalize the model, the following assumption will hold
1. Operation cycle times, Setup times, and non-operation times are equal to $n_{oj}$ machines
2. Batch quantities of all parts or products processed through the same number of machines, so that $n_{oj} = n_o$

Therefore, the simplified equation for MLT will be

$$MLT = n_o(S_{ut} + QC_t + T_{no})$$  \hspace{1cm} \text{ix}

Apply equation (ix) to Job shop production in which batch size is one ($Q = 1$)
We shall have equation (x),

$$MLT = n_o(S_{ut} + C_t + T_{no})$$  \hspace{1cm} \text{x}

Apply equation (ix) to Mass production in which batch size is very large ($Q = \text{Large}$)
In this case, the MLT becomes operation cycle time for the machine after the setup has been completed and production begins

$$MLT = QxC_t$$  \hspace{1cm} \text{xi}

Apply equation (ix) to flow line production in which batch size is maximum ($Q = \text{Max}$)
In this case, the entire production line is set up in advance, and non-operation time between processing steps is simply the transfer time $T_t$
We shall have,

$$MLT = n_o(T_t + MaxT_{no}) = n_oC_t$$  \hspace{1cm} \text{xii}

Therefore, Equation (xii) becomes

$$(T_t + MaxT_{no}) = C_t$$  \hspace{1cm} \text{xiii}

Since the number of stations is equal to the number of operations ($n=n_o$), then equation (xii) will be

$$MLT = n(T_t + MaxT_{no}) = nC_t$$  \hspace{1cm} \text{xiv}
2.4 Costs of Manufacturing Operations

It is essential to estimate the cost of manufacturing a component before the actual production and this can be done during the phase design and it is very vital to optimize alternative strategies for the manufacturing in order to control the product cost. Manufacturing costs are affected by many factors and some of them are direct attribute to the manufacturing process and the desired level of tolerance [31].

There are two basic categories of Manufacturing Costs

1. Fixed Costs – This cost remains constant for any output level
2. Variable Costs – This cost varying in proportion to production output level

Adding both fixed and variable costs, the expression is represented in equation (xv) as shown in figure 3.

\[ TC = \sum (FC + VC(Q)) \]

Where,

TC = Total Costs

FC = Fixed Costs (this include, equipment, taxes, building, etc.)

VC = Variable Costs (this include, utilities, labour, materials, etc.)

Q = Output level

Figure 3: Breakeven point for Manual and Automated Total Cost of Production
In modern manufacturing systems, low production costs, high product quality and manufacturing flexibility are vital ingredients to competitiveness. On this note, the manufacturing cost is always a key and fundamental concern [1].

Alternative Classification of Manufacturing Cost is as shown in figure 4 as enumerated thus:

1. Direct Labour Cost – These can be in form of salary, wages, stipends and benefits paid to workers
2. Materials Costs – These are costs used for the procurement of raw materials
3. Overhead Costs – These are total expenses used for the running of a day-to-day manufacturing firm.
   a. Factory Overhead
   b. Corporate Overhead

![Flowchart of Manufacturing Costs](image)

**Figure 4:** Flowchart of Manufacturing Costs

### 2.5 Overhead Rates

According to Groover [32] overhead rates can be in form of Factory and Corporate Overhead rate as shown in equations (xvi & xvii)

Factory Overhead Rate (FOHR)

\[ \text{FOHR} = \frac{\text{FOHC}}{\text{DLC}} \]  

Corporate Overhead Rate (COHR)
\[ COHR = \frac{COHC}{DLC} \]  

Where,

DLC = Direct Labour Costs  
FOHC = Factory Overhead Costs  
COHC = Corporate Overhead Costs

2.6 Cost of Using the Equipment

Hourly total cost of the personnel-machine system is the sum of personnel cost and machine cost according to Groover [32] as depicted in equation (xviii)

\[ C_{mp} = \sum(C_L(FOHR_L + 1) + C_M(FOHR_M + 1)) \]  

Where,

\[ C_L = \text{Labour Cost, /hr} \]  
\[ C_{mp} = \text{Machine-Personnel hourly cost, /hr} \]  
\[ C_M = \text{Machine rate, /hr} \]  
\[ FOHR_L = \text{Labour factory overhead rate} \]  
\[ FOHR_M = \text{Machine factory overhead rate} \]  

2.7 Performance of a Partially Automated Flow Line

The total costs of operating the automated flow Line (\( C_{col} \)) which include capital, overhead and labor can be expressed mathematically in equation (xix):

\[ C_{col} = n_{ms}C_{ms} + n_{as}C_{as} + C_{at} \]  

Where,

\[ C_{col} = \text{Total cost of operating the line (Capital, overhead, and labor)} \]  
\[ n_{ms} = \text{Total number of workstations on the flow line} \]  
Therefore,

The total number of workstations on the flow line = number of automated flow line + number of manual flow line which be expressed in equation (xx)
\[ n_{WS} = n_{as} + n_{ms} \]  

\( n_{as} = \) Number of Automated flow stations 
\( n_{ms} = \) Number of Manual Flow Stations 
\( C_{ms} = \) Operational Cost per manual station 
\( C_{as} = \) Operational Cost of Automated Station 
\( C_{at} = \) total cost of automatic transfer mechanism (this will be used for all the lines be in automatic or manual) to transfer the workpiece.

### 2.8 Average Production Time

In order to calculate average production time (\( P_{At} \)), the ideal cycle time (\( C_t \)) will be added to average downtime per cycle (\( d_{At} \)) and the expression represented in equations (xxi) and (xxii)

\[ P_{At} = C_t + Fd_{At} \]  

\[ P_{At} = C_t + n_{as}P_{as}d_{At} \]  

Where,

\( F=n_{as}P_{as} = \) Breakdown Work index for partial automation 
\( P_{as} = \) Probability for breakdown station of automatic workhead (this may varying at different station) 
\( n_{as}= \) Number of Automatic workstation and it is assumed that there is no breakdown at manual station

### 2.9 The Cost per unit Produced

The cost per unit produced (\( C_{pu} \)) can be expressed mathematically in equation (xxiii)

\[ C_{pu} = C_M + C_{col}xP_{At} + C_{tool} \]  

By substituting the value for \( C_{col} \) and \( P_{At} \), gives equation (xxiv)

\[ C_{pu} = C_M + (n_{ms}C_{ms} + n_{as}C_{as} + C_{at})(C_t + n_{as}P_{as}d_{At}) + C_{tool} \]  

Where \( C_{tool} \) is a tooling cost which can be neglected (\( C_{tool} = 0 \))

### 3.0 Cost Modelling of Full Automation
Cost modeling can be described as the methods, techniques or procedures used to forecast and estimate the cost of a proposed project. Cost models will help the Managers or Business owner to plan for certain activities and processes before execution especially in the Automated system.

Automated systems are systems used to control a process without the interference of Human Beings. These systems are used mainly to increase profit, increase productivity, to reduce lead time as well as to increase product quality among the others. Cost modellings are associated with the varieties of costs which include:

1. Maintenance Cost ($C_{m1}$)
2. Design Cost ($C_{d1}$)
3. Programmer Cost ($C_{p1}$)
4. Material Cost ($C_{M1}$)
5. Installation Cost ($C_{i1}$)
6. Management Costs ($C_{n1}$)
7. Training Cost ($C_{t1}$)
8. Consulting Cost ($C_{c1}$)
9. Operating Cost ($C_{01}$)
10. Cost of the temporary staff to install and run the System ($C_{ts1}$)

The mathematical model representing the total cost of automation ($C_{model}$) is expressed in eqn (xxv):

$$C_{model} = \sum (C_{d1} + C_{M1} + C_{i1} + C_{m1} + C_{c1} + C_{t1} + C_{01} + C_{p1} + C_{n1} + C_{ts1})$$  

### 4.0 Conclusions

Premised on the research gap which sorts to find the total economic cost of production in an automated factory, a generalized mathematical model for partial and full automation that handle either fixed, flexible and programmable automation operations with regards to cost due to the cycle time for production, manufacturing lead time, cost of overall manufacturing, production time and equipment usage. An operational model capable of handling the different categories of the aforementioned automation processes in a typical mass production factory is derived and presented in this article. Whereas, the authors focus, is drawn to the most possible path of achieving break even in manufacturing operation processes, the model developed tracks logistics costs and estimates the maximum cost total in the production line for automated process plant. More importantly, the proposed model has the potential to incorporate exigent cases from externally incurred cost accrued from vendor services, professional consultation, and etcetera. It is envisaged the model will improve operational cost effectiveness over choices made on the design and maximize profit in the long run. A model which is capable of estimating the lowest operational cost of a production process executable in an automated factory in presented in this work.

Over the years cost estimation in production operations and service delivery have posed significant challenges to industrial managers on the price of acquiring materials and cost of labour in other to ascertain the final value of the goods or service. The current trend in industries
stimulated by the integration of advanced technological assistance in businesses is pivotal for increased productivity and caused new companies to design and build automated work-flow factories, while old companies seek to combine automated processes and machine operations with manual labour. However, there exists a gap in the know-how, and best approach to estimate production cost in automation operations. While very few software exist to be used, they become too expensive, inaccessible and mostly limited to the designer's scope. Hence, a holistic model that will address Automation Cost Estimating Systems (ACES) in imperative for small, medium and large-scale industrial managers as covered in this article.

Compliance with ethical standards:

Conflict of interest: The authors declare that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work.

Reference

[1] Shehab, E. M. and Abdalla, H.S., (2001). An intelligent Knowledged based system for product Cost Modelling. International Journal of Advanced Manufacturing Technology.

[2] Weustink, I., Brinke, E.T., Streppel, A., & Kals, H. (2000). A generic framework for cost estimation and cost control in product design. Journal of Materials Processing Technology. (103), http://doi.org/10.1016/S0924-0136(00)00405-2.

[3] Chen, M. Y., & Chen, D. F. (2002). Early cost estimation of strip-steel coiler using BP neural network. Beijing. First international Conference on Machine Learning and Cybernetics. http://doi.org/10.1109/ICMLC.2002.1167420.

[4] Nagahanumaiah, R. B., & Mukherjee, N. (2005). An integrated framework doe die and mold cost estimation using design features and tooling parameters. International journal for Advanced Manufacturing Technology, (26), 1138-1149. http://doi.org/10.1007/S00170-004-2084-9.

[5] Daniyan I. A., Omokhuale A. M, Aderoba A. A., Ikumapayi O. M, Adaramola B. A. (2017): Development and performance evaluation of organic fertilizer machinery, Cogent Engineering (Taylor & Francis). DOI: 10.1080/23311916.2017.1364044

[6] Oyinbo, S.T, Ikumapayi O.M, Ajiboye J.S and Afolalu S.A. (2015) Numerical Simulation of Axisymmetric and Asymmetric Extrusion Process Using Finite Element Method., International Journal of Scientific & Engineering Research, Vol. 6 (6). June-2015 pp1246-1259.

[7] Imhade P. Okokpujie, O. O. Ajayi, S. A. Afolalu, A. A. Abioye, E.Y. Salawu, M. O. Udo, U. C. Okonkwo, K. B. Orodu and O. M. Ikumapayi (2018): Modeling and Optimization
of Surface Roughness In End Milling of Aluminium Using Least Square Approximation Method and Response Surface Methodology, International Journal of Mechanical Engineering and Technology 9(1), 2018. pp. 587–600. Scopus Index

[8] Afolalu S.A., Ajayi O.O, Ikumapayi, O.M and Adejuyigbe, S.A (2015). Modeling and Simulation of Wave load on Periodic Support for Isolation System of Offshore Platform, International Journal of Scientific & Engineering Research, Vol. 6 (5), May-2015, pp 441-447, http:

[9] Bankole.I. Oladapo, S. Abolfazl Zahedi, F. Vahidnia, O.M. Ikumapayi, Muhammad U. Farooq (2018). Three-dimensional finite element analysis of a porcelain crowned tooth. Beni-Suef University Journal of Basic and Applied Sciences. https://doi.org/10.1016/j.bjbas.2018.04.002

[10] Imhade Princess Okokpuye, Omolayo M. Ikumapayi, Ugochukwu C. Okonkwo, Enesi Y. Salawu, Sunday A. Afolalu, Joseph O. Dirisu, Binna N. Nwoke, and Oluseyi O. Ajayi. (2017). Experimental and Mathematical Modeling for Prediction of Tool Wear on the Machining of Aluminium 6061 Alloy by High Speed Steel Tools. Open Eng. 2017; 7:461–469. DOI: https://doi.org/10.1515/eng-2017-0053

[11] Cunningham, C.R; Wikshåland, S; Xu, F; Kemakolam, N; Shokrani, A.; Dhokia, ; and Newman, S.T. (2017): Cost modelling and sensitivity analysis of wire and arc additive manufacturing. 27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017. Procedia Manufacturing 11: 650 – 657

[12] Zhang, Y., & Fuh, J. (1998). A neural network approach for early cost estimation of packaging products. Computers industrial Engineering, 34(2), 433 – 450. http://doi.org/10.1016/S0360-8352(97)00141-1

[13] Jiao, J., & Tseng, M. M. (1999). A pragmatic approach to product costing based on standard time estimation. International journal of operations and production Management, 19(7), 738-755. http://doi.org/10.1108/01443579910271692

[14] Bendul, J. and Apostu, V. (2017) : An Accuracy Investigation of Product Cost Estimation in Automotive Die Manufacturing. International Journal of Business Administration, Vol 8, No. 7, pp 1-15

[15] Kumar,G and Bhatia, P. . (2014). Automation of Software Cost Estimation using Neural Network Technique. International Journal of Computer Applications, 98(20), 11–17.

[16] Aderoba Adeyemi. (1997). production economics model for job shops. International Journal of Production Economics, 52, 257–263.

[17] Allen, A. J., & Swift, K. G. (1990). Manufacturing process selection and costing, 204, 143–148.

[18] Bengtsson, M., & Kurdve, M. (2016). Machining Equipment Life Cycle Costing Model with Dynamic Maintenance Cost. Procedia CIRP, 48, 102–107. https://doi.org/10.1016/j.procir.2016.03.110
[19] Jiang, L., Walczyk, D., Mcintyre, G., & Kin, W. (2016). Cost modeling and optimization of a manufacturing system for mycelium-based biocomposite parts, 41, 8–20.

[20] Windmark, C., Gabrielson, P., Andersson, C., & Ståhl, J. E. (2012). A Cost Model for Determining an Optimal Automation Level in Discrete Batch Manufacturing, 3, 73–78. https://doi.org/10.1016/j.procir.2012.07.014

[21] Buonasera, T. Y. (2015). Modeling the costs and benefits of manufacturing expedient milling tools. Journal of Archaeological Science, 57, 335–344.

[22] Favi, C., Germani, M., & Mandolini, M. (2017). Analytical cost estimation model in High Pressure Die Casting. Procedia Manufacturing, 11(June), 526–535. https://doi.org/10.1016/j.promfg.2017.07.146

[23] Muratori, M., Ledna, C., Mcjeon, H., Kyle, P., Patel, P., Kim, S. H., Edmonds, J. (2017). Cost of power or power of cost: A U.S. modeling perspective. Renewable and Sustainable Energy Reviews, 77(April), 861–874.

[24] Orisanmi B.O, et al. (2017). Cost of Corrosion of Metallic Products in Federal University of Agriculture, Abeokuta. International Journal of Applied Engineering Research, 12(24), 14141–14147.

[25] Hayashi, Y., & Cole, M. (2002). Automated cost analysis of a parallel maxims segments sum program derivation. Parallel Processing Letters, 12(1), 95–111.

[26] Li, Y., & Burns, C. M. (2017). Modeling Automation With Cognitive Work Analysis to Support Human-Automation Coordination. Journal of Cognitive Engineering and Decision Making, 11(4), 299–322. https://doi.org/10.1177/1555343417709669

[27] Risør, B. W., Lisby, M., & Sørensen, J. (2017). Cost-Effectiveness Analysis of an Automated Medication System Implemented in a Danish Hospital Setting. Value in Health, 20(7), 886–893. https://doi.org/10.1016/j.val.2017.03.001

[28] Salmi, A., David, P., Blanco, E., & Summers, J. D. (2016). Computers & Industrial Engineering A review of cost estimation models for determining assembly automation level. Computers & Industrial Engineering, 98, 246–259. https://doi.org/10.1016/j.cie.2016.06.007

[29] Wadud, Z. (2017). Fully automated vehicles: A cost of ownership analysis to inform early adoption. Transportation Research Part A, 101, 163–176. https://doi.org/10.1016/j.tra.2017.05.005

[30] Primrose P L, Hoey J, Leonard R. (2006) "A Methodology for Incorporating the ‘Companywide’ Benefits of Material Requirements Planning within a Discounted Cash Flow Investment Analysis", Proceedings of the Institution of Mechanical Engineers, Part B: Management and engineering manufacture, 2006
[31] Dong, Z. (1997). Tolerance Synthesis by Manufacturing Cost Modeling and Design Optimization. Advanced Tolerance Techniques, Editted by Hong-Chao Zhang, John Wiley & Sons, Inc, 1997, pp 233-260.

[32] Groover M. (2011). Manufacturing models and metrics. In: Automation, production systems, and computer-integrated manufacturing. 3rd ed. New Delhi: PHI Learning Private Limited; 2011. p. 58–62.