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FAULT TREE ANALYSIS OF FLY-OUTS IN METAL LATHE MACHINE OPERATIONS

Abstract: *The most probable accident in lathe machining has been identified to be fly-outs. This study aim at determining the causal factors leading to fly-out accidents during lathe machining operations and subsequently determine the probability of occurrence of fly-out accident. Fault tree analysis (FTA) was used to identify risk factors. Boolean algebra equations were used to analyse the probability of fault occurrence. Monte Carlo simulation was carried out using OpenFTA software and the output of 1000 iterations was compared with the output of Boolean algebra. Safety intervention alternatives were evaluated by comparative analysis of before and after implementation of safety measures. Twenty four (24) minimum cut sets comprising of 21 basic events and 3 undeveloped events were identified. The top event has probability of 0.748 signifying high likelihood for fly-out. Monte Carlo simulation gave lower and upper bounds probabilities of 0.725 and 0.773, respectively. The event of the chuck key not pulled out of the chuck before machining begins was however noted to have the highest contribution to the occurrence of fly-out accident. The result of safety intervention alternatives revealed that the probability of fly-out becomes 0.192 with a safety benefit of N27, 800 after the first tier implementation. Other tiers of safety interventions will see the probability of fly-out go further down. By this, safety engineer has a scale for effectiveness of respective safety intervention programmes.*

Key words: fly-out, accident, safety, intervention, lathe, machine, operation.

INTRODUCTION

Over the last three decades there were development in the maintenance and servicing industries, of a distinctive approach to hazards and failures that cause loss of life and property. This approach is commonly called `loss prevention'. It involves putting much greater emphasis on technological measures to control hazards, accidents and on trying to get things right first time. The rapid development of new technology has essentially changed the nature of work and has increased the complexity of systems within many industries. Hence, the world becomes increasingly complicated. These complex systems require a combination between technical and human subsystems (Kletz, 1999). In this sense, the failure of a subsystem can often cause the failure of the entire system. Moreover, catastrophic breakdowns of these systems create serious threats, not only for those within the organization, but also for the surrounding public. Simultaneously, the accidents that occur in workplaces have also become more complex and in some cases more frequent.

In fact, increased technological dependence has led to bigger accidents, involving more people, and greater damage to property and the environment. It has become clear that such vulnerability does not originate from just human error, technological failures, or environmental factors alone. Rather, it is the fixed organizational policies and standards which have repeatedly been shown to predate the catastrophe. Therefore, safety practitioners in recent years have begun to focus on the organizational values that might enhance risk and crisis management and safe performance in industries complex conditions. Some scholars (Simon and Leik 1999) believed that culture and technology actually go hand in hand. Culture consists of attitudes, perceptions, beliefs, and values, which need to be set in context. In the face of new mandates, it is believed that culture can play a vital role in helping organizations respond to the many safety challenges.

Most accidents in Nigerian industries are a direct result of not adhering to their established safety procedures, as well as lack of strong safety culture, safe working conditions, and employees' safe work attitudes and actions (Oyesola and Kola, 2014). Thus, the participation of all employees including managers and non-managers is vital in policymaking, establishing, and implementing a feedback system that drives continuously toward safety improvement in industrial companies to achieve a successful safety program. It must be mentioned that safety culture has an important role in reducing occupational accidents in industry. The identification of areas of vulnerability and of specific hazards is of fundamental importance in loss prevention and safety. There is now available a whole battery of hazard identification methods which may be used to solve these problems (DOSH, 2008).

Human by default are susceptible to making errors and infact neglecting certain safety rules and regulations, a consequence of which could be so deadly both to themselves, their co-workers, machineries and the environment resulting in a possible loss of lives, property and revocation of their operating licenses. However, human error is just an aspect of safety as environment, hardware and other factors also serve as links to safe machining operations. With noise, numerous machines and a handful of people on the plant floor, one mistake can result in a serious incident that can cause personal injury and wreak havoc on production. Each year, millions of workers suffer from non-fatal workplace injuries, resulting in an annual cost of billions of dollars (EASHW, 2004). Outside the primary objective of reducing injuries to people or property, proving the value of a safety system is an ongoing challenge for safety professionals and risk managers. Many find it difficult to financially justify discretionary investments in safety-related trainings intended to reduce work-related injuries.

Safety investments greatly reduce cost of repairs. With an up-front investment in safety programs and safeguarding systems, the financial and employee impact of incidents that occur in the facility can be significantly diminished. Having realized this huge capital investment on safety, evaluation and re-evaluation to justify this huge spending are necessary as well as analyzing historical accidents of ranging proportions from fatal, minor to near-misses with a view to tailor the existing safety policy to achieve the ultimate goal for which the entire concept of safety is based; to preserve lives and properties (SESR, 2012).

This paper seeks to conduct a hazard/causal factor identification analysis capable of leading to fly-outs on lathe machine operations and to evaluate in quantitative terms using Fault Tree Analysis (FTA). Also to determine the probability of failure by considering elemental failures that can lead to Fly-outs and recommend safety interventions, and to evaluate the effectiveness of such interventions. It will also examine how the probability of failure is affected by various safety interventions.

MATERIALS AND METHOD

Having consulted and reviewed series of safety reports associated to lathe operations of a case study workshop; this research seeks to consider *fly-outs* during machining operations. These fly-outs envisage the possibility of tool fly out during a machining process, work piece fly out as well as the effect of discontinuous chips (swarf) removal during operations that ranges from turning, shaping etc. to achieve the objectives using the tools described in sections 2.1, 2.2 and 2.3.

Fault Tree Analysis

Fault tree analysis (FTA) is used to investigate potential faults, its modes and causes and to quantify their contribution to system unreliability in the course of product design. FTA is a technique by which conditions and factors that can contribute to a specified undesired event are identified and organized in a logical manner and represented pictorially (Jane, 2012). FTA has been widely successfully used in various fields. Tetlow and Jenkins (2005) used it to visualise the importance of human factors for safe diving with closed-circuit rebreathers. Kumar and Sneh, (2011) applied it to analyse the reliability of piston manufacturing system while Hu et al., (2011) used FTA for hierarchical diagnosis model and sequential control of manufacturing system to mention a few.

Boolean Algebra Equations

With human Experts judgments, Boolean algebra equations were used to analyse the probability of fault occurrence. Boolean algebra is a devise for dealing mathematically with philosophical propositions which have only two possible values of TRUE or FALSE represented by the digits “0” and “1”. It deals with the rules which govern various operations between the binary variables. “AND” operation describes events which can occur IF and only IF two (2) or more other events are TRUE. “OR” Operation describes events which can occur IF at least one (1) of the other events are TRUE (Ovidiu, 2003).

Monte Carlo Simulation

Monte Carlo simulation of the fault tree was conducted using the commercial software called “OpenFTA”. 1000 Iterations were carried out and the output compared with the Boolean algebra equations. Monte Carlo simulation, also called probability simulation, is a technique widely used to understand the impact of risk and uncertainty in forecasting models. It can tell based on how the ranges of estimates are created, how likely the resulting outcomes are. Monte Carlo techniques are often the only practical way to evaluate difficult integrals or to sample random variables governed by complicated probability density functions (Cowan, 2011). OpenFTA is an advanced tool for FTA. With OpenFTA, superior graphical user interface, fault trees can be constructed and modified with ease (FSCL, 2005).

Safety Intervention Measure

The safety intervention alternatives were evaluated by comparative analysis of before and after implementation of safety measures. Safety intervention for the respective faults was examined to evaluate how well and how much the measure can bring about a reduction in the probability of the top-event. This tailors the research into the subject matter of identifying hazard conditions, sequence of accident, qualitative and quantitative evaluation, and finally, an evaluation of the case-study's safety intervention programme to see how the intervention would reduce the probability of accident occurrence. The overall evaluation of safety in line with the subject matter of fly-out incorporates quantitative and qualitative evaluations to channel a course for safety intervention. This can be viewed as a case of sensitivity analysis whereby the effect of safety evaluation is examined on the probability of fly-out accidents to see how respective intervention reduces the probability of top-event occurrence.

To ascertain the effectiveness of a safety intervention program, an appraisal of the case-study safety intervention programme was carried out by firstly identifying areas that require intervention and by making appropriate recommendation.

RESULTS

Lathe Hazard Identification and Consequences Analysis

Safety concerns on lathe operations were considered under various headings of major lathe hazards and the commonest causes of death and injury from metal lathes were evaluated. These include:

- Entanglement of clothing in moving parts such as drive gears, chucks, lead and feed screws, and the work piece;
- Being hit by loose objects on the lathe such as chuck keys, tools or swarf;
- Entanglement from inappropriate tooling and polishing techniques;
- Being struck by a workpiece that has not been adequately secured in the lathe or is oversized.

Figure 1 shows the zones of metal turning lathe hazards. Six hazard zones have been identified. Each zone was analyzed to include the possible consequence (e.g. entanglement) of the hazard and their recommended controls. Table 1 contains a comprehensive hazard identification and consequences analysis of identifiable hazards during lathe operations

Qualitative Safety Evaluation: Fault Tree Construction

The child root for a tool fly-out is as represented Figure 2. Seven causal factors capable of triggering a tool fly-out during machining operations on a lathe were identified as chuck fault, workpiece holding fault, tool post fault, coolant fault, improper operating speed, safety guards fault, swarf guard and chuck guard and Improper mounting.

Further analysis of root/intermediate events into minimum cut sets i.e. basic events that could lead to the child node event; twenty four (24) basic events are identified and presented in fault tree in Figure 3. Probabilities for the identified failures are presented in Table 2.

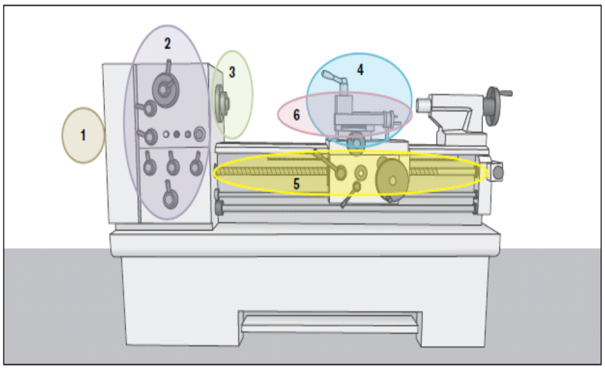

Figure 1. *Hazard Zones of Metal Turning Lathe Machine*

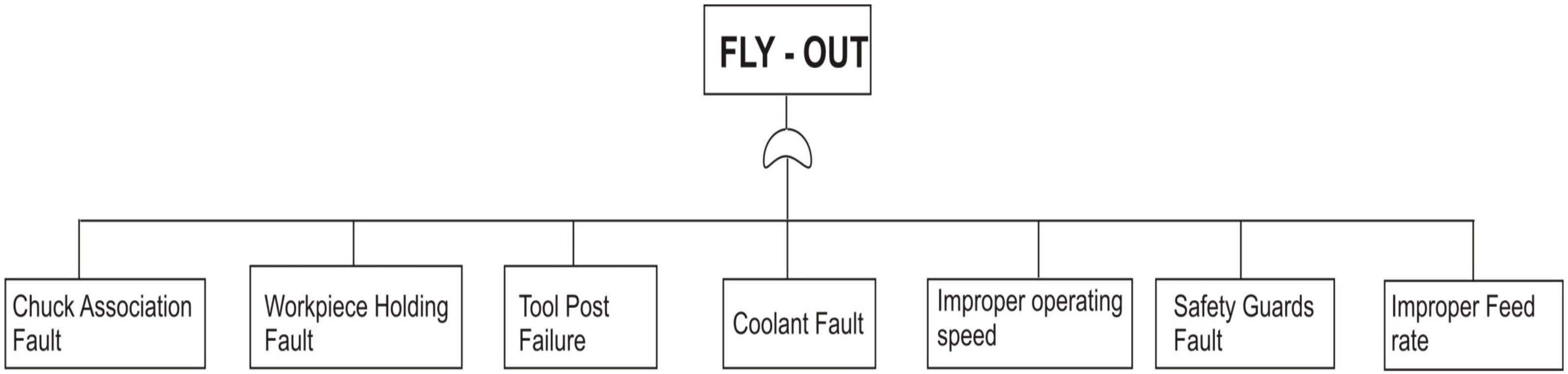

Figure 2: Hazards/causal Factors Capable of Triggering a Tool Fly-out During Machining Operations on a Lathe.

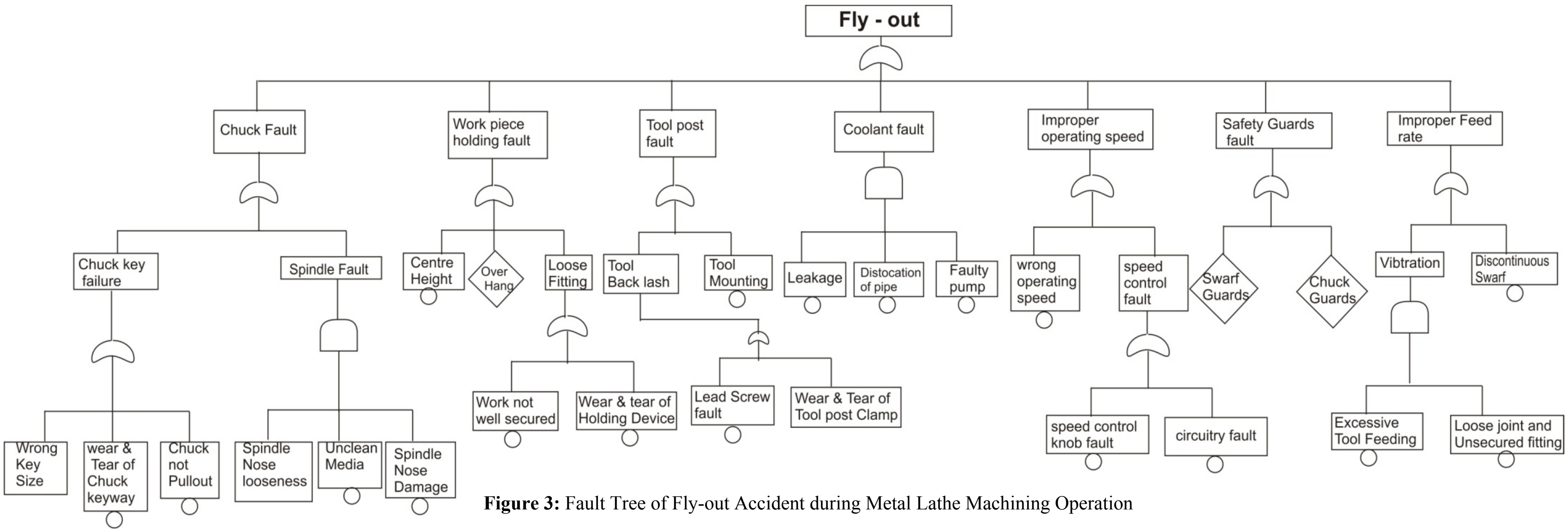

Figure 3: Fault Tree of Fly-out Accident during Metal Lathe Machining Operation

Table 1. *Lathe Operations Hazards and Consequences*

Hazards	**Possible consequence**
Zone 1	
Workpiece beyond the headstock.	During spindle rotation, bar can bend and strike machinists nearby.
Zone 2	
Exposed drive mechanisms (pulley, belts, gears).	Machinists can become entangled in pulleys, belts or gears when lathe is in operation.
Lathe controls can only be reached by passing hand through working zone.	Machinists can become entangled in unguarded drive mechanisms, chuck, chuck assembly or workpiece when the lathe is in operation.
Lack of function markings on controls.	Machinists can activate incorrect controls resulting in an unplanned function.
Placements of controls do not follow the machining process.	Machinists can activate incorrect control resulting in an unplanned function.
Unsecured tools and objects stored or placed on the headstock.	Stored objects can fall onto the spinning chuck and be propelled at the operator or nearby machinists
Zone 3	
Exposed chuck.	Machinists can become entangled on uneven surface of chuck or workpiece when spinning.
Chuck key left in chuck.	Machinists near lathe can be struck by key when projected from the lathe.
Jaws of chuck unable to clamp workpiece securely.	Machinists can be struck by workpiece not securely held in the chuck.
Chuck has not been adequately secured to the spindle.	Machinists can be struck by chuck not securely held in the spindle.
Mounting and removing heavy chucks and face plates.	Machinists can sustain musculoskeletal or crushing injuries when changing heavy chucks and faceplates.
Use of a chuck that is not compatible with lathe and/or task specifications.	Use of incorrect chucks can result in the chuck or workpiece becoming loose and striking machinists
Chucks and face plates used on the lathe are damaged or have catch points.	Machinists can become caught on chucks and faceplates that are poorly maintained or have protrusions.
Oversized workpiece in self-centering chuck (three-jaw chuck)	Chuck jaws in full extension to allow for oversized workpieces can be propelled from the lathe when operated.
Zone 4	
Objects (e.g. cutting tools) unsecured on carriage (including tool post) or swarf	Unsecured objects can become projectiles when the lathe is started, possibly striking machinists.
Worn or damaged tools being used on the lathe.	Use of worn or damaged tools can result in tool failure and can become projectiles or create irregular or long cuttings that can lead to lacerations.
Zone 5	
Exposed lead and feed screws (assessment of risk will need to include the speed at which the lead and feed screws travel).	Machinists can become entangled in exposed lead and feed screws when the lathe is in operation, particularly if the lathe is being used by a number of users with various levels of experience.
Zone 6	
Unguarded protrusions on the workpiece.	Machinists can become entangled on protrusions on the workpiece being turned.
Coupling and clamps used on the lathe are damaged or have catch points.	Machinists can become caught on coupling and clamps that are poorly maintained or have protrusions.
Unsupported workpieces.	Unsupported workpieces can become loose, striking machinists.
Machining process produces continuous or unraveled cuttings.	Machinists can become entangled in turning cuttings.
Removing metal shavings, cuttings and swarf from machining area with hands.	Unprotected handling of shavings, cutting and swarf can result in lacerations.
Neighboring workspaces are exposed to swarf, cuttings or workpieces during the machining process.	Swarf, cuttings or workpieces can become projectiles and strike nearby machinists, causing injuries such as lacerations and fractures.
Frequent traffic (human and machinery) passing through the work area near the operator.	While operating the lathe, the operator can be bumped or startled by passing traffic, causing the operator to come into contact with the lathe.
Incorrect methods used for polishing workpieces with emery cloth.	Machinist can become entangled in the lathe.
Others	
Lack of or poorly placed emergency stop button/pedal that results in immediate standstill of lathe operation.	Operator is unable to stop the lathe in case of an emergency.
Loose clothing, cuffed or rolled back sleeves, neckties, jewelry (including watches) and long hair.	Loose clothing, accessories and hair can become entangled in moving parts of the lathe, chuck assembly or workpiece.
Environment	
Inappropriate type and position of lighting.	The flashing effect of fluorescent light can make a spinning lathe appear to have stopped. This can lead to machinists' entanglement. Lighting placed over the lathe can be struck by projectiles from the machining process. Machinists nearby can be injured by the light shattering.
Untidy and unorganized working Environment.	Machinists can slip or trip on cutting oils, swarf or cuttings that are not cleaned from the floor. Machinists can also trip over lathe parts or workpieces that are not returned to storage areas.

Probability of failure P (F) =
1 - (1 - V_1) x (1 - V_2) x (1 – V_3) x (1 – V_4) x (1 – V_6) x (1 – V_{10}) (1 – V_{12}) x (1 – V_{13}) x (1 – V_{15}) x (1 - V_{17}) x (1 – V_{19}) x (1 – V_{20}) x (1 – V_{21}) x (1 – V_{22}) x (1 – V_{23}) x (1 – V_{24}) x (1 – V_8 * V_{14} * V_{18}) x (1 – V_{11}* V_{16}) x (1 – V_5 * V_7 * V_9)

P (F) = 1 – (0.251561 * 0.999849)
= 1 - 0.251523
= 7.484772E-001
= 0.748

Table 2 presents the faults and the respective probabilities of faults. The following faults namely: Chuck Associated Fault, Work holding Fault, Tool Post Fault, Coolant Fault, Wrong Machining Speed, Safety Guards and Improper Feed rate Fault respectively, are the faults having the capability to initiate the occurrence of fly-out. The probabilities of these faults are 0.720001, 0.050, 0.035, 0.0000005, 0.015, 0.020 and 0.01515, respectively. The probabilities of these faults reveal that *chuck associated failure* has the highest likelihood/probability of initiating the top event having a probability of failure of 0.720001, followed by *work holding faults* with a probability of 0.050, *tool post failure* with a probability of 0.035, *safety guards failure* with a probability standing at 0.20 followed by the fault from *improper feed rate* with a probability of 0.01515 and FINALLY faults from *wrong machining speed* and *coolant fault* having probabilities of 0.015 and 0.0000005, respectively. It is noteworthy that coolant failure has the least probability and hence, it has the least capacity of initiating a fly-out during lathe operations

Further presented in Table 3 is the result of basic event analysis and their respective importance represented as a percentage of the overall probability of top-event. A graphical representation is also provided in Figure 4. The result here reveals that V_4 (event of chuck not being pulled out before machining operation begins) has the highest importance (93.52%) and if any safety intervention is to be justified, it must be centralized on the primary event with the highest importance. V_4 represents the *first tier of safety intervention*. Furthermore, V_2, V_3, V_6, V_{15}, V_{17} and V_{20} having an importance of 2% apiece are the next areas of priority (*second tier of intervention*) in terms of safety intervention. However, V_1, V_9, V_{11}, V_{13}, V_{21}, V_{22}, V_{23} and V_{24} have lesser importance, with their importance standing at 1.34% apiece. V_{13} with an importance of 0.67% can also be merged with the events of 2%. These events are hence assigned for *third tier intervention*. Other events have 0% importance and no major intervention is needed.

Table 2. *Probabilities of Failure of Basic Events*

`	Event ID	Type	Description	Failure rate/Unit time.
V_1	CCT	Basic Of Event	Circuitry Fault	0.010
V_2	CHG	Underdeveloped	Chuck Guard Fault	0.015
V_3	CHT	Basic	Centre Height Fault	0.015
V_4	CPO	Basic	Chuck Not Pulled Out	0.700
V_5	DP	Basic	Dislocation of Pipe	0.010
V_6	DSWARF	Basic	Discontinuous Swarf	0.015
V_7	PUMP	Underdeveloped	Faulty Pump	0.010
V_8	LB	Basic	Spindle Nose Looseness	0.010
V_9	LK	Basic	Leakage	0.005
V_{10}	LSF	Basic	Leadscrew Fault	0.010
V_{11}	LSNESS	Basic	Loose Joints and Unsecured Fitting	0.015
V_{12}	OH	Underdeveloped	Overhang	0.010
V_{13}	SCKF	Basic	Speed Control Knob Fault	0.005
V_{14}	SND	Basic	Spindle Nose Damage	0.010
V_{15}	SWG	Underdeveloped	Swarf Guard	0.015
V_{16}	TFEEDING	Basic	Excessive Tool Feeding	0.010
V_{17}	TM	Basic	Tool Mounting	0.015
V_{18}	UN	Basic	Unclean Media	0.010
V_{19}	WK	Basic	Wrong Key Size	0.010
V_{20}	WNS	Basic	Work Not Well Secured	0.015
V_{21}	WS	Basic	Wrong Operating Speed	0.010
V_{22}	WT1	Basic	Wear And Tear of Chuck Keyway	0.010
V_{23}	WT2	Basic	Wear And Tear of Holding Device	0.010
V_{24}	WT3	Basic	Wear And Tear of Tool Post Clamps	0.010

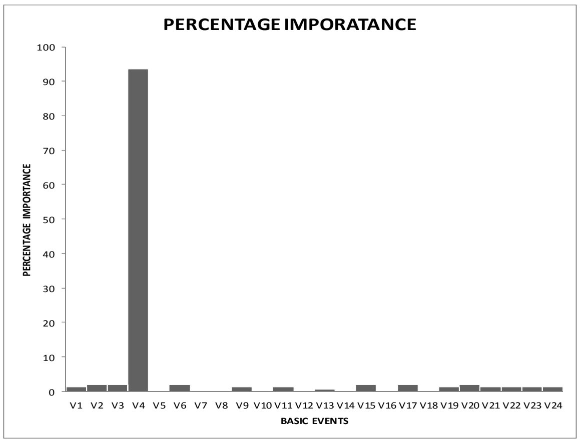

Figure 4. *Probabilities of Basic Events*

Table 3. *Primary Event Analysis*

Event	Description	Importance (%)	Failure contribution
V_4	Chuck Not Pulled Out	93.52	7.000000E-001
V_2	Chuck Guard Fault	2.00	1.500000E-002
V_3	Centre Height Fault	2.00	1.500000E-002
V_6	Discontinuous Swarf	2.00	1.500000E-002
V_{15}	Swarf Guard	2.00	1.500000E-002
V_{17}	Tool Mounting	2.00	1.500000E-002
V_{20}	Work Not Well Secured	2.00	1.500000E-002
V_1	Circuitry Fault	1.34	1.000000E-002
V_9	Leakage	1.34	1.000000E-002
V_{11}	Loose Joints and Unsecured Fitting	1.34	1.000000E-002
V_{19}	Wrong Key Size	1.34	1.000000E-002
V_{21}	Wrong Operating Speed	1.34	1.000000E-002
V_{22}	Wear And Tear of Chuck Keyway	1.34	1.000000E-002
V_{23}	Wear And Tear of Holding Device	1.34	1.000000E-002
V_{24}	Wear And Tear of Tool Post Clamps	1.34	1.000000E-002
V_{13}	Speed Control Knob Fault	0.67	5.000000E-003
V_{10}	Leadscrew Fault	0.02	1.500000E-004
V_{16}	Excessive Tool Feeding	0.02	1.500000E-004
V_5	Dislocation of Pipe	0.00	5.000000E-007
V_7	Faulty Pump	0.00	1.000000E-006
V_8	Spindle Nose Looseness	0.00	5.000000E-007
V_{12}	Overhang	0.00	5.000000E-007
V_{14}	Spindle Nose Damage	0.00	1.000000E-006
V_{18}	Unclean Media	0.00	1.000000E-006

Safety Intervention Benefits

Table 4 is a tabulation of the basic events, their respective description and safety intervention recommendation. In this present study, safety interventions were categorised as follow:

- First tier safety intervention; training, supervision, inspection and procurement and installation (self-ejecting chuck key procurement etc.);
- Second tier safety intervention; preventive maintenance and quality of maintenance;
- Third tier safety intervention; intermittent check-listing and supervision

Assuming the expected cost of fly-outs injury ranges from simple laceration to complete facial surgery is ₦50, 000, the resulting citicatility C of a lathe machining fly-outs injury is:

$$C = P(F)(₦50{,}000)$$

$$= 0.748 \times 50000$$

$$= ₦37{,}400$$

The event that machinist are expertly trained, supervised and monitored that chuck keys are not left in the chuck before machining starts would reduce the probability of "chuck not pulled out" from 0.7 to 0.21. However, the other failure modes could still occur and the probability of fly-outs reduces to 0.192 with a new criticality of ₦9, 600. The benefits or savings of the implementation of the safety intervention is the decrease in the criticalities i.e.

$$Safety\ benefits = ₦37{,}400 - ₦9{,}600$$

$$= ₦27{,}800$$

Monte Carlo Simulation

Using "OpenFTA", the simulation results are as presented below:

1. Number of primary events = 24;
2. Number of tests (iterations) = 1000;
3. Number of system failures = 976;
4. Probability of at least one component failure = 0.768 (exact) and
5. Probability of top event = 0.749 (+/- 0.024) i.e. 0.725 and 0.773.

The events, descriptions and failure contributions are shown in Table 5.

The Boolean algebra analysis reveals that the top-event has a probability of 0.748; however, the Monte Carlo analysis offered a range of probability in which the top event can happen (0.725 and 0.773). It is noteworthy at this stage that the Boolean algebra result is within the range of probabilities obtained using Monte Carlo simulation. However, the percentage importance as well as the fault contribution of some cut-sets suffered a reduction while some remained constant after 1000 simulations.

Table 4. *Basic Events and Nature of Safety Intervention and Recommendation*

Event	Description	Safety Intervention and Recommendation
V_1	Circuitry Fault	Pro-active preventive maintenance of the machine, electrical component inspection and check-listing.
V_2	Chuck Guard Fault	Installation of chuck guards Employers must ensure guarding does not stop workers using the lathe in a safe manner or block the view of the task. Where multiple chucks are used, guarding should cover the swing of the lathe, not the size of a chuck.
V_3	Centre Height Fault	Use a bar feed tube to hold workpiece that extends beyond the headstock. Guard bar feed weights with hinged covers extending to the floor. Modify the lathe speeds (RPM) to ensure bar will not bend when machined. Install barriers to stop workers entering space around headstock.
V_4	Chuck Not Pulled Out	Adequate training of machinists and proper supervision of machining operations. Use of spring-loaded chuck key. Use of self-ejecting chuck key. Use of extended key design that stops interlocked guard being lowered when inserted in chuck.
V_5	Dislocation of Pipe	Intermittent checklist should be drafted to monitor the position of the pipe per time during machining operations.
V_6	Discontinuous Swarf	Manufacturer specified federates should be adhered to and swarf should be cleared timely.
V_7	Faulty Pump	Preventive maintenance.
V_8	Spindle Nose Looseness	Pro-active preventive maintenance and specific level inspection for vibration. Use of retaining nut with left-hand thread.
V_9	Leakage	Training to ensure machinists pay absolute concentration on the task before them so they can notice leakages on time.
V_{10}	Leadscrew Fault	Where appropriate, ensure lead and feed screws are guarded
V_{11}	Loose Joints and Unsecured Fitting	Preventive maintenance and proper inspection practices. Retightening of bolts, couplings and replacement of worn out parts.
V_{12}	Overhang	Use workpieces of minimum length to reduce the amount of bar protruding from headstock. Use of fixed or travelling steadies to support long, slender workpieces between centres or to support outer end of long piece held in chuck for drilling or boring.
V_{13}	Speed Control Knob Fault	Preventive maintenance. Ensure control functions are clearly displayed. Ensure operators are adequately trained in what order to use controls.
V_{14}	Spindle Nose Damage	Use of retaining nut with left-hand thread and tightened with a torque wrench to manufacturers specification.
V_{15}	Swarf Guard	Ensure swarf guards are installed and made operatable so as not to hinder machining operations. Also, ensure swarf handles and buckets are used when cleaning swarf, shaving and cuttings from lathe
V_{16}	Excessive Tool Feeding	An excessive tool feeding set up vibration and transmits the impulse to the tool post, the chuck and the spindle thereby loosening the couplings. Machinists should be trained to feed at optimal levels to avoid the impulse transfer.
V_{17}	Tool Mounting	Ensure worn or damaged tools are removed and not used. Ensure the tool is properly secured on the tool post.
V_{18}	Unclean Media	Proper maintenance work and housekeeping.
V_{19}	Wrong Key Size	Use of manufacturer specified key size for respective chucks.
V_{20}	Work Not Well Secured	Training; Chuck type and size selection should be given priority in line with the machining operation to be carried out. Rightful selection of chuck key to ensure the chuck jaws fully grip the work piece.
V_{21}	Wrong Operating Speed	Training of machinists to adhere to RPMs as stipulated in the manufacturer's manual.
V_{22}	Wear And Tear of Chuck Keyway	Ensure worn or damaged tools are removed and not used.
V_{23}	Wear And Tear of Holding Device	Ensure worn or damaged tools are removed and not used.
V_{24}	Wear And Tear of Tool Post Clamps	Ensure worn or damaged tools are removed and not used.

Table 5. *Monte Carlo Simulation Results*

Event	Description	Importance (%)	Failure contribution
V_4	Chuck Not Pulled Out	93.34	7.00E-01
V_{15}	Swarf Guard	2.56	1.92E-02
V_2	Chuck Guard Fault	2.46	1.84E-02
V_6	Discontinuous Swarf	2.36	1.77E-02
V_{11}	Loose Joints and Unsecured Fitting	2.25	1.69E-02
V_{19}	Wrong Key Size	1.54	1.15E-02
V_{20}	Work Not Well Secured	1.43	1.08E-02
V_{23}	Wear And Tear of Holding Device	1.43	1.08E-02
V_1	Circuitry Fault	1.34	1.15E-02
V_{17}	Tool Mounting	1.33	9.98E-03
V_9	Leakage	1.23	9.21E-03
V_3	Centre Height Fault	1.13	8.45E-03
V_{24}	Wear And Tear of Tool Post Clamps	1.13	8.45E-03
V_{22}	Wear And Tear of Chuck Keyway	1.02	7.68E-03
V_{13}	Speed Control Knob Fault	0.61	4.61E-03
V_5	Dislocation of Pipe	0.00	0.00E+00
V_7	Faulty Pump	0.00	0.00E+00
V_8	Spindle Nose Looseness	0.00	0.00E+00
V_{10}	Leadscrew Fault	0.00	0.00E+00
V_{12}	Overhang	0.00	0.00E+00
V_{14}	Spindle Nose Damage	0.00	0.00E+00
V_{16}	Excessive Tool Feeding	0.00	0.00E+00
V_{18}	Unclean Media	0.00	0.00E+00
V_{21}	Wrong Operating Speed	0.00	0.00E+00

Table 6 provides the difference between Boolean algebra result and Monte Carlo result for 1000 iterations.

Table 6. *Deviation of Boolean Algebra Result and Monte Carlo Simulation Results*

Event	Description	Importance (%)	Failure contribution
V_1	Circuitry Fault	0	0
V_2	Chuck Guard Fault	0.46	0.23
V_3	Centre Height Fault	-0.87	-0.435
V_4	Chuck Not Pulled Out	-0.18	-0.00192
V_5	Dislocation of Pipe	0	0
V_6	Discontinuous Swarf	0.36	0.18
V_7	Faulty Pump	0	0
V_8	Spindle Nose Looseness	0	0
V_9	Leakage	-0.11	-0.08209
V_{10}	Leadscrew Fault	-0.02	-1
V_{11}	Loose Joints and Unsecured Fitting	0.91	0.679104
V_{12}	Overhang	0	0
V_{13}	Speed Control Knob Fault	-0.06	-0.08955
V_{14}	Spindle Nose Damage	0	0
V_{15}	Swarf Guard	0.56	0.28
V_{16}	Excessive Tool Feeding	-0.02	-1
V_{17}	Tool Mounting	-0.67	-0.335
V_{18}	Unclean Media	0	0
V_{19}	Wrong Key Size	0.2	0.149254
V_{20}	Work Not Well Secured	-0.57	-0.285
V_{21}	Wrong Operating Speed	-1.34	-1
V_{22}	Wear And Tear of Chuck Keyway	-0.32	-0.23881
V_{23}	Wear And Tear of Holding Device	0.09	0.067164
V_{24}	Wear And Tear of Tool Post Clamps	-0.21	-0.15672

DISCUSSION

Accident and safety upheavals offer a great risk to organizational life in terms of preserving its much revered assets such as lives and properties. Machining operations can be entirely safe. However, humans may not adhere strictly to instructions and procedures. The idea of safety engineering hence, is not to make a vulnerable machinist pay the dare price of life threatening injury, rather, keeping him safe despite his shortfalls and from surrounding hazards. The nature of accidents has been discovered to be a chain reaction, with each basic event setting off a bigger fault, transmitting the fault over and in that manner causing an undesirable event - accident.

The hazard analysis conducted by this study on lathe operations using root cause analysis of accidents recorded for a case study of machine shop (Etherton et al., 2015), and expert narrations to determine the pattern and mode of accidents incumbent on lathe operations revealed that fly-outs and entanglements are the most widely occurring accidents. With FTA of the causal factor; basic and intermediate events that could lead to a Fly-out, twenty four (24) basic events were identified. They include: Circuitry fault, Chuck Guard fault Centre-Height fault, Chuck not pulled out, Dislocation of pipe, Discontinuous swarf, Faulty pump, Spindle nose looseness, Leakage, Leadscrew fault, Loose joints and unsecured fittings, Overhang, Speed control knob fault, Spindle nose damage, Swarf guard, Excessive tool feeding, Tool mounting, Unclean media, Wrong key size, Work not well secured, Wrong operating speed, Wear and Tear of Chuck keyway, Wear and Tear of Holding device, Wear and Tear of tool post clamps.

In this present study, the use of Boolean algebra showed that the top event has probability of 0.748 for occurrence. A Monte Carlo simulation was equally carried out in furtherance to this cause, the top event was observed to have an lower bound and upper bound of 0.725 and 0.773 respectively. This therefore captured the probability obtained using Boolean algebra. Evidently, the value obtained from the use of Boolean algebra is well in within the results obtained via the use of Monte Carlo simulation. The event of the chuck key not being pulled out of the chuck before the commencement of machining was noted to have highest probability of occurrence (0.7) hence, it has the highest contribution to the top-event. Work-holding and loose fitting are other faults having high contribution to the occurrence of top-event. Percentage importance of respective faults was used as the basis for the application of safety intervention. Safety interventions identified were training, safety equipment procurement, guards, condition monitoring, inspection and preventive maintenance, intermittent check-listing and machining operation supervision. With the implementation of the first tier of safety intervention (training), the FTA revealed that if chuck-fly out can be entirely eliminated by training machinists to use the right size of chuck and chuck key, and remove the chuck key before the commencement of machining operation, the probability of chuck not pulled out is 0.21, then the probability of top event occurring will be considerably lesser and will only amount to 0.192. Consequently, the criticality of lathe machining fly-out injury decreases from ₦37, 400 to ₦9, 600 with a safety benefit of ₦27, 800.

CONCLUSION

The study conducted a Fault Tree Analysis in metal lathe machining operation. Twenty four basic events leading to the occurrence of fly-out accident were identified. This includes Circuitry fault, Chuck Guard fault Centre-Height fault, Chuck not pulled out, Dislocation of pipe, Discontinuous swarf, Faulty pump, Spindle nose looseness, Leakage, Leadscrew fault, Loose joints and unsecured fittings, Overhang, Speed control knob fault, Spindle nose damage, Swarf guard, Excessive tool feeding, Tool mounting, Unclean media, Wrong key size, Work not well secured, Wrong operating speed, Wear and Tear of Chuck keyway, Wear and Tear of Holding device, Wear and Tear of tool post clamps.

The result of FTA revealed that fly-outs are the most widely occurring accidents during metal lathe machine operations with a probability of 0.748. Monte Carlo analysis of the FTA shows the probability of fly-outs having lower and upper bounds of 0.725 and 0.773, respectively. The event of the chuck key not being pulled out of the chuck before the commencement of machining was noted as the event with the highest probability of occurrence contributing to the top-event. Safety intervention alternatives were implemented and the result revealed that the probability of fly-out becomes 0.192 with a safety benefit of ₦27, 800. Increased safety benefits can be achieved if other safety intervention alternatives are further implemented.

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ANALIZA STABLA GREŠAKA ZBOG LETEĆIH ČESTICA STRUGOTINE PRI RADU SA STRUGOM ZA OBRADU METALA

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Sažetak: *Najverovatniji uzrok nesreće pri radu sa strugom za obradu metala su leteće čestice strugotine. Cilj ovog istraživanja je utvrđivanje uzročnih faktora koji dovode do nezgoda zbog letećih čestica strugotine pri mašinskoj obradi, i određivanje verovatnoće nastanka ovog tipa nesreće. Analiza stabla grešaka (eng. Fault Tree Analzysis - FTA) se koristi za identifikaciju faktora rizika. Jednačine Bulove algebre su korišćene za analizu verovatnoće nastanka greške. Izvedena je simulacija Monte Karlo korišćenjem softvera OpenFTA a rezultat nakon 1000 ponavljanja je poređen sa rezultatima Bulove algebre. Alternativn bezbedonosne intervencija su procenjene uporednom analizom pre i posle sprovođenja mera zaštite. Identifikovana su dvadeset četiri (24) minimalna rezanja u kojima može nastati 21 osnovni događaj i 3 nerazvijena događaja. Najbitniji događaj ima verovatnoću 0.748 i označava veliku verovatnoću da će se doći do letenja strugotine. Simulacija Monte Karlo je dala donje i gornje granice verovatnoće od 0,725 i 0,773, respektivno. Ukoliko se odrvrtač glave struga ne izvuče pre početka mašinske obrade, ovaj događaj najviše doprinosi nastanku nesreće koja je prouzrokavana letećom strugotinom. Rezultat alternativnih zaštitinih intervencija je pokazao da verovatnoća raste na 0,192 a korist zbog primenjenjih mera bezbednosti postaje N27, 800 nakon prvog nivoa implementacije. Ostali nivoi bezbednosnih intervencija pokazuju da verovatnoća nezgode usled leteće strugotine opada. Imajuću ovo u vidu, inženjer zaštite može izabrati neki od odgovarajućih programa zaštite na osnovu skale efektivnosti.*

Ključne reči: čestice leteće strugotine, nesreća, bezbednost, intervencija, strug, mašina, operacija.