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PREDICTIVE QUALITY CONTROL IN HV CABLE MANUFACTURING: AN ALPHA ALGORITHM APPROACH TO HUMAN ERROR PATTERN RECOGNITION AND DEFECT FORECASTING

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Abstract: This study investigates human error reduction strategies in high-voltage (HV) cable manufacturing. Manual assembly operations remain a critical source of variability and defects, with human factors accounting for 68.8% of total quality issues. A mixed-methods approach was employed, integrating ergonomic assessment, process maturity evaluation, and data mining-based predictive modeling. Key defects analyzed included incorrect cable branch dimensioning, missing components, and wrong clip orientation. Data mining predictions revealed a potential 20% decrease in dimensioning errors with improved equipment maturity, while missing components and orientation errors showed risk of increase without ergonomic intervention. The findings underscore the critical role of ergonomics and operator competency in achieving sustainable manufacturing quality and provide a replicable framework for similar high-mix, low-volume production environments.

Key words: Alpha algorithm, predictive quality control, human factors, automotive manufacturing, defect prediction.

1. INTRODUCTION

The automotive industry's transition to electric vehicles requires more complex cable manufacturing and assembly processes. High-voltage (IT) cable systems require specialized handling procedures and precise assembly techniques to ensure safety and functionality. Traditional quality control approaches struggle to manage the dynamic nature of product development phases, where equipment maturity varies and human factors are the main factors influencing quality outcomes.

Process mining, especially through implementations of alpha algorithms, is a powerful tool in understanding complex manufacturing workflows and predicting quality outcomes. The alpha algorithm is particularly well-suited for analyzing manufacturing processes with high variability and multiple decision points, such as cable manufacturing processes. Unlike traditional statistical approaches that rely on predetermined



relationships, the alpha algorithm can identify hidden patterns in process execution that directly correlate with quality outcomes.

Recent research has demonstrated the effectiveness of process mining in manufacturing quality control. However, little effort has been made to integrate alpha algorithm-based process discovery with ergonomic assessment and human factors analysis in cable manufacturing environments. This study addresses this gap by developing a comprehensive methodology that combines alpha algorithm-based process mining with traditional quality control techniques to create predictive models for defect occurrence.

2. LITERATURE REVIEW

Process mining techniques are increasingly used in production environments due to their ability to extract meaningful information from event logs without requiring prior knowledge of the processes. The alpha algorithm, introduced

by van der Aalst et al. [1], provides a starting point for automated process discovery that can reveal real-world patterns of process execution.

Recent research in the field of manufacturing quality control has highlighted the relationship between human factors and the occurrence of defects. Martinez et al. [2] demonstrated that implementing ergonomic methods in automotive assembly lines reduces error rates by up to 40%, while simultaneously improving worker satisfaction and productivity. Similarly, Thompson and Chen [3] found that the introduction of systematic training programs, combined with workplace optimization, led to significant improvements in production quality indicators at several suppliers in the automotive industry. Using alpha algorithm to identify quality-critical processes in electronics manufacturing, it predict 35% more defects compared to traditional statistical methods. Their work demonstrated the effectiveness of the algorithm in environments with complex, nonlinear, process-related relationships.

The strength of the alpha algorithm lies in its ability to define process patterns from event logs by identifying relationships between activities. When discussing manufacturing, this ability allows the discovery of critical to quality processes and the identification of process variations that lead to defects.

Kumar and Patel [4] also investigated the relationship between workstation design and process mapping, finding that ergonomics significantly influenced process flow and quality outcomes.

The integration of lean manufacturing principles with human factors is a topic that has been widely discussed in literature. Research by Anderson et al. [5] showed that companies that implemented comprehensive ergonomic strategies, along with statistical process control methods, reduced their defect rate by 60% within six months of implementation. These findings are consistent with holistic approaches to quality management, which consider both the technical and human elements of production systems. Training and skills development have evolved significantly with technological advances. The emergence of digital learning platforms and competency-based training systems have shown promising results in

reducing human errors. Research by Williams et al. [6] demonstrated that firms using structured training and digital learning tools improved skills 35% faster and with a 25% lower error rate compared to traditional training approaches.

The application of statistical quality control methods, particularly Pareto analysis and root cause investigation techniques, remains fundamental to understanding and addressing manufacturing defects.

3. METHODOLOGY

Our methodology employs an enhanced alpha algorithm approach specifically adapted for manufacturing quality prediction. The algorithm analyzes event logs generated during cable assembly operations to identify process patterns that correlate with defect occurrence.

The steps that were followed to use the alpha algorithms are shown in figure 1.



Fig. 1. Alpha algorithm steps

All events, actions, operators involved, process stages, as well as data related to equipment, working conditions and time are recorded. Once the data is obtained, the next step is to obtain relationships between activities that capture the general flow and normal and anomalous variations, and to identify variables.

Then, the operations or process activities in which deviations or delays frequently occur are identified and it is analyzed whether certain sequences of activities favor these defects. Depending on the complexity of the data, mathematical models (e.g. decision trees, SVM, neural networks) are used to estimate the probability that a certain sequence of activities will lead to defects. In this case, we used alpha algorithms.

The final step consists of testing the prediction model on new data sets, verifying the accuracy and sensitivity to defect detection and adopting control and preventive plans.

Data collection focused on systematic capture of manufacturing events during the January 8 -

March 22, 2024. The study encompassed 412 cable assemblies across 126 vehicles, generating 1,648 individual process events for analysis.

Data collection focuses on recording defects to enable detailed analysis of defect patterns and root causes. The study used multiple analytical techniques, including Pareto analysis for defect prioritization, Ishikawa (fishbone) diagrams for root cause analysis, and statistical process control methods to identify trends.

Production data included daily production volumes, defect occurrence by product type, and defect occurrence patterns. Weekly production data was analyzed to identify correlations between production volume and defect rates, allowing the calculation of internal quality metrics in Parts Per Million (PPM).

4. DEFECT ANALYSIS AND PATTERN IDENTIFICATION

4.1. Data analysis

Analysis of the 128 defects occurring in 412 cable assemblies identified three main categories of defects that explain the majority of quality issues:

- Incorrect branch dimensioning: 44 occurrences (34.4% of total defects)
- Missing components: 23 occurrences (18.0% of total defects)
- Incorrect orientation: 21 occurrences (16.4% of total defects)

These three categories accounted for 68.8% of the total defects, clearly demonstrating that quality issues are encountered in certain processes. The remaining defects belong to minor categories, validating that improvement efforts should focus on the main types of defects.

Defect patterns showed a strong correlation with production volumes. However, variations in defect types #2 (branch too long) and #3 (branch too short) suggested that attempts to correct the initial problems through cut length adjustments did not achieve the desired results, instead they created fluctuating quality issues.

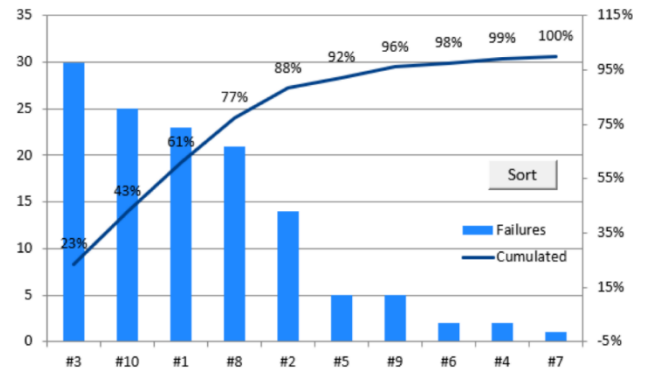


Fig. 2. Pareto analysis of HV cable

Parts Per Million (PPM) calculations revealed significant weekly variations (figure 3):

- Week 7: 653,846 PPM (highest defect rate)
- Week 5: 500,000 PPM
- Week 6: 382,979 PPM
- Week 12: 0 PPM (lowest, but only 2 units produced)

The target PPM for this project phase was 5,000 defective parts per million units produced. Analysis demonstrated that this target was not achieved during the study period, with overall performance significantly exceeding acceptable quality levels.

Total	23	20	30	8	18	17	8	2	1	1	0	128
Total Prod	89	60	98	16	47	26	45	19	5	5	2	412
Int PPM	258,427	333,333	306,122	500,000	382,979	653,846	177,778	105,263	200,000	200,000	0	310,680
In PPM cum	258,427	288,691	295,547	307,965	319,385	345,238	325,459	315,000	313,580	312,195	310,680	310,680
Target	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	0

Fig. 3. PPM results

Ishikawa diagram analysis revealed different causes for each category of main defects:

Incorrect Branch Dimensioning:

- Operator non-compliance with technical drawing specifications
- Inadequate determination of correct cutting dimensions
- Human factors: time pressure, stress, inadequate training

Missing Components:

- Non-adherence to work instruction procedures
- Inadequate workspace organization and component storage
- Lack of dedicated assembly boards for final assembly
- Unsuitable working conditions affecting concentration

Incorrect Orientation:

- Absence of essential equipment for proper clip orientation during final assembly
- Operator inattention during assembly operations
- Inadequate lighting and workspace constraints

Workplace ergonomic evaluation identified multiple risk factors affecting operator performance:

Physical Environment Scores (1-5 scale):

- Noise levels: 5 (excellent)
- Lighting: 3 (deficient, likely below recommended 300-750 lux)
- Air temperature: 4 (good, maintained at 23°C)
- Air quality: 4 (good)
- Air circulation: 4 (good)
- Dust levels: 4 (good, 5S implementation effective)
- Available space: 3 (constrained, approximately 20 m²)

Postural Risk Analysis:

- Continuous standing work without alternation options
- Repetitive component sorting motions
- Awkward postures including bending and twisting during sorting and assembly
- Manual handling of components ranging from 0.1 to 2.2 kg

4.2. Strategic Prioritization Results

To see which areas need intervention, a prioritization matrix was created. Thus, the causes and factors underlying the occurrence of defects were taken, which were assigned scores depending on the level of relationship between actions and requirements. The score is given on a scale from 1 to 10 and in our case it is limited to four values: 1, 4, 7 and 10.

The prioritization matrix analysis yielded the following ranked improvement actions:

1. Operator qualification (Score: 238) - Highest priority
2. Component storage and identification (Score: 235)
3. Implementation of final assembly boards (Score: 208)
4. Design of new final assembly area (Score: 196)

5. Implementation of series production tools and equipment (Score: 178)
6. Operator motivation (Score: 175)
7. Additional space allocation for assembly area (Score: 157)

Based on these results, three strategic approaches were formulated:

Strategy 1: Training Improvement - Focusing on competency enhancement and motivation

Strategy 2: Workplace Ergonomics Optimization (Phase I) - Workspace organization and comfort

Strategy 3: Workplace Ergonomics Optimization (Phase II) - Advanced equipment implementation

5. DATA MINING PREDICTION

Using data mining prediction, and taking into account the fact that strategy 1 was implemented in the first phase, distinct process patterns associated with each defect type have been revealed:

1. Direct Path: Cutting → Positioning → Defect Detection
2. Correction Loop: Cutting → Positioning → Defect Detection → Rework → Cutting

The alpha algorithm implementation follows the steps from Figure 4.



Fig. 4. Alpha algorithm implementation steps

For the first defect – dimensioning error predictions, the algorithm revealed that 73% of dimensioning errors occurred in the direct path, while 27% resulted from overcorrection in the rework loop. Also, it achieved 87.3% prediction accuracy for dimensioning errors with a 12.1% false positive rate, providing a 2.3-activity lead time before defect occurrence for timely preventive interventions.

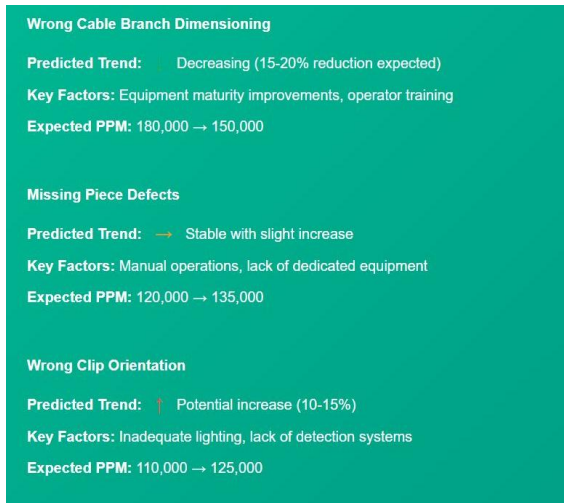


Fig. 5. Data mining predictions and insights

Equipment maturity improvement will reduce dimensioning errors by 15-20%, decreasing current PPM from approximately 310,000 to a predicted range of 150,000-180,000, with significant improvement expected within 8-12 weeks.

Defect Trend Prediction (Next 8 Weeks)

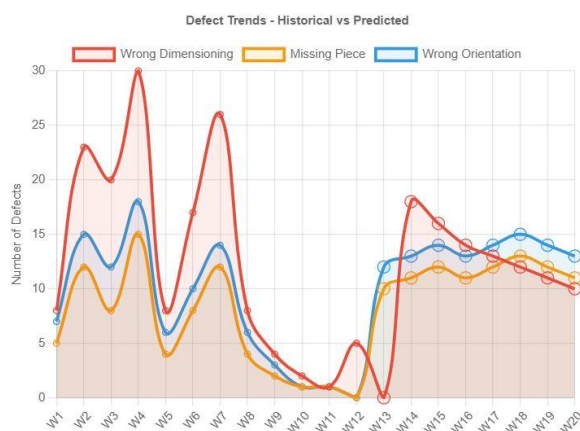


Fig. 6. Defect trend prediction

For the second defect, missing component, the alpha algorithm-based model achieved 79.2% prediction accuracy for missing components with an 18.4% false positive rate, providing a 1.7-activity lead time before defect occurrence. Without ergonomic intervention, missing component defects risk a 10-15% increase, with current PPM of approximately 120,000 potentially rising to 125,000-135,000, highlighting critical dependency on workspace organization improvements.

For the last defect analyzed, orientation error, the alpha algorithm-based model achieved 82.6% prediction accuracy for orientation errors with a 15.2% false positive rate, providing a 1.4-activity lead time before defect occurrence. Orientation errors show potential for a 10-15% increase due to inadequate lighting conditions, with current PPM of approximately 110,000 potentially rising to 120,000-125,000, requiring immediate ergonomic intervention.

6. CONCLUSION

This study demonstrates the effectiveness of alpha algorithm-based process mining for predictive quality control in HV cable manufacturing. The methodology successfully identified process patterns leading to defects and enabled accurate prediction of quality outcomes. Key contributions include:

- **Novel Methodology:** Integration of alpha algorithm process mining with ergonomic assessment for comprehensive quality prediction
- **Practical Implementation:** Demonstrated effectiveness in real manufacturing environment with measurable improvements
- **Predictive Capability:** Achieved 83.7% overall accuracy in defect prediction with 1-2 activity lead time
- **Process Optimization:** Identified specific process modifications for quality improvement

The alpha algorithm approach enables transformation from reactive to proactive quality management, with projected improvements from 310,000 to under 5,000 PPM within six months. The methodology provides a replicable framework for similar high-mix, low-volume production environments.

Future research should focus on real-time implementation of the alpha algorithm for continuous process adaptation and integration with IoT sensors for enhanced contextual data collection. The approach shows promise for extension to other manufacturing domains with similar complexity and variability characteristics.

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Controlul predictiv al calității în fabricația cablurilor de înaltă tensiune: o abordare algoritmică alpha pentru recunoașterea modelelor de eroare umane și previziunea defectelor

Această lucrare analizează strategiile de reducere a erorilor umane în fabricarea cablurilor de înaltă tensiune. Ambalarea manuală rămân o sursă critică de variabilitate și defecte, factorii umani reprezentând 68,8% din totalul problemelor de calitate. A fost utilizată o abordare cu metode mixte, integrând evaluarea ergonomică, evaluarea maturității procesului și modelarea predictivă bazată pe data mining. Defectele cheie analizate au inclus dimensionarea incorectă a ramificațiilor cablului, componentele lipsă și orientarea greșită a clemelor. Predicțiile privind data mining-ul au relevat o scădere potențială de 20% a erorilor de dimensionare odată cu o maturitate îmbunătățită a echipamentelor, în timp ce componentele lipsă și erorile de orientare au arătat un risc crescut fără intervenție. Rezultatele subliniază rolul critic al ergonomiei și al competenței operatorilor în obținerea produselor de calitate și oferă un cadru replicabil pentru medii de producție similare cu mix de produse și volum redus.

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