From Human Error Prevention to QFD-Based Preventive System Design in Thailand's Agricultural and Automotive Manufacturing Systems

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Received: January 9, 2026 / Revised: February 27, 2026 / Accepted: March 25, 2026

***Abstract*—Traditional agricultural and automotive manufacturing systems still rely heavily on manual operations and maintenance, making human error a major source of process instability, product quality variation, and equipment failure. In Thailand, educational pathways strongly shape workforce capability in these industries. Technical and Vocational Education and Training (TVET) programs emphasize hands-on skills, equipment operation, and practical problem-solving, whereas general academic education focuses primarily on theoretical knowledge, often resulting in weaker alignment with operational requirements. In this study, human error is defined as a systemic issue arising from interactions among Man, Machine, Material, and Method (4M), rather than as isolated individual mistakes. Quality Function Deployment (QFD) and the House of Quality (HoQ) translate manufacturer and business owner requirements into explicit workforce competency specifications to prevent human error. By linking organizational priorities with skill-based design requirements, the proposed framework supports a shift from corrective responses to preventive system design, enhancing reliability, safety, and sustainability in agricultural and automotive manufacturing environments.**

***Index Terms*—Human Error Prevention, Agricultural Manufacturing Systems, Quality Function Deployment (QFD), House of Quality (HoQ), Technical and Vocational Education (TVET), Maintenance Engineering**

I. Introduction

Agricultural manufacturing industries transform raw agricultural products into materials suitable for food, industrial, and consumer applications. Among these industries, starch-based manufacturing represents a vital link between agriculture and downstream production, supplying inputs for food, pharmaceuticals, packaging, and bio-based products. While technological advances have enabled high efficiency and automation in modern plants, much of agricultural manufacturing—particularly starch, sago, and cassava processing—still relies on traditional factories characterized by manual operations and human-centered decision-making. In these environments, humans remain central to daily production and maintenance activities. Operators and technicians handle machine setup, material handling, inspection, adjustment, and repair. As a result, human error significantly affects process stability, product quality, equipment reliability, and safety in agricultural manufacturing systems. Unlike discrete manufacturing sectors, agricultural processing uses biological raw materials that vary in moisture content, particle size, and contamination levels. This variability increases process complexity and places additional demands on workers. Small human errors—such as incorrect machine settings, delayed maintenance, unnoticed vibration, or improper cleaning—can propagate through the production chain, leading to quality loss, energy waste, or equipment damage [1]-[3].

A. Human Error Overview

In traditional factories, these errors are often treated as isolated incidents rather than indicators of systemic weaknesses. Agricultural manufacturing systems can be examined using the 4M framework: Man, Machine, Material, and Method. Within this framework, human error intersects with all dimensions. Workers (Man) possess experiential knowledge but may lack formal training in error

prevention. Machines (Machine) are often aging and not designed to tolerate improper use or maintenance mistakes. Materials (Material), being natural and variable, increase the impact of incorrect handling or processing. Lastly, methods (Method) often rely on tradition rather than standardized procedures, making it difficult to detect and correct deviations early. While previous studies have addressed productivity improvement, equipment redesign, and material utilization in agricultural industries, human error—particularly in routine operations and maintenance—has received limited attention. Errors are commonly addressed only after breakdowns or quality failures occur, reinforcing a corrective rather than preventive approach. This reactive practice limits the long-term sustainability and competitiveness of agricultural manufacturing industries [4].

B. Literature Review

Historically, Thailand's labor market has been shaped by demographic transition and structural economic change. In earlier decades, a large share of the workforce was concentrated in agriculture and informal sectors, where demand for certified technical competencies or standardized vocational qualifications was limited. However, as Thailand industrialized and integrated into global supply chains, the need for technical skills increased, particularly in manufacturing and service sectors. Despite this shift, relatively fewer students pursue technical career pathways than general academic tracks, creating a persistent mismatch between labor market demands and available technical competencies. The Technical and Vocational Education and Training (TVET) system has long been recognized as a key mechanism for addressing this skills gap. OECD reports indicate that approximately 14% of Thai secondary students are enrolled in TVET programs, higher than the ASEAN average of 8% but still insufficient to fully meet industry demand. While TVET graduates generally show stronger employment outcomes and wage premiums than those with only general secondary education, the supply of vocational graduates remains insufficient to meet growing demand for skilled technical workers in key sectors [5].

Despite these enrollment trends, Thailand continues to struggle with a mismatch between educational outputs and labor market demand. Employers report shortages of skilled technicians and operators—particularly in industrial sectors— a skills mismatch remains a significant barrier to productivity and competitiveness. Rapid technological change and evolving job requirements intensify the problem, demanding not only basic technical skills but also strong problem-solving abilities, critical thinking, and digital literacy [6].

Thailand's labor market is undergoing structural change driven by digital transformation and automation. AI and related technologies are increasingly automating routine tasks, while new roles require stronger digital and cognitive competencies. However, AI cannot fully replace human labor. Manufacturing and maintenance activities still require human judgment, hands-on skills, and experiential knowledge that cannot be fully codified into algorithms. Operational settings involve variability and uncertainty, demanding contextual decision-making and practical problem-solving. In addition, creativity, craftsmanship, and professional responsibility remain human-centered capabilities that automated systems cannot replicate. While AI improves efficiency through data analysis and system monitoring, sustainable industrial development depends on integrating AI technologies with skilled workers to enhance performance, reduce human error, and strengthen system reliability [7]-[8].

Despite ongoing policy efforts to promote vocational education, recent data show a continuous decline in TVET enrollment in Thailand. National statistics (2018-2025) (Fig. 1) indicate that total enrollment peaked at approximately 1,028,961 students in 2563 before declining steadily to 898,442 students in 2568. This represents a decline of about 130,519 students, or 12.7% over five academic years. The downward trend suggests more students are shifting from vocational pathways to general academic education. This situation raises concerns about the future supply of technically skilled workers. A continued reduction in TVET enrollment may worsen skill shortages in operational and maintenance roles, increasing the risk of human error in manufacturing sectors that rely heavily on practical technical competencies.

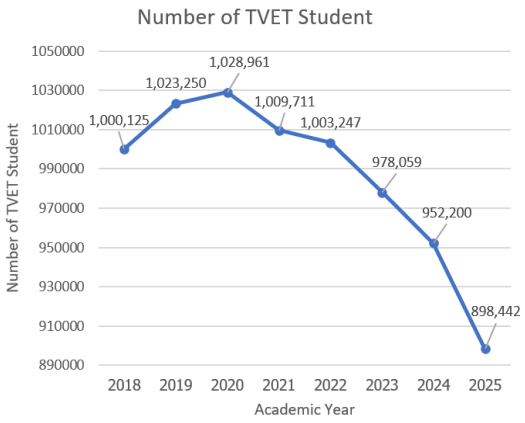

Fig. 1. Number of TVET students vs. academic year [10]

Therefore, enhancing the attractiveness of vocational education and integrating emerging technologies, such as AI, into training programs are

essential for maintaining industrial reliability and long-term competitiveness [9]-[10].

C. Human Error Examples

Human error also plays a significant role in agricultural machinery accidents, particularly with tractors and other equipment. A case study in Italy examined how human error affects agricultural tractor operations and integrated these findings into risk assessment procedures for vineyard cultivation. The research highlighted that operator failures—such as incorrect handling, delayed responses, and misjudging hazardous conditions—substantially contribute to accidents and injuries, despite stringent safety regulations. The study emphasized the need for user-centered approaches in hazard analysis and safety interventions to mitigate risks associated with human error during agricultural machinery operation, including hazard identification and ergonomic factors that influence operator performance [11].

D. Thailand's Workforce Structure

Thailand's workforce structure clearly divides Technical and Vocational Education and Training (TVET) graduates from those from general academic pathways (upper secondary and non-engineering university programs). TVET curricula emphasize hands-on training, machine operation, maintenance practices, and compliance with Standard Operating Procedures (SOPs), while general academic education prioritizes theoretical knowledge and progression to higher education. This divergence directly affects workforce readiness in manufacturing environments where error prevention depends on practical competence [12], [13].

E. Current Trend

Recent evidence from both automotive manufacturing and agricultural industries indicates that workers with vocational or technical backgrounds are better prepared to perform error-sensitive operational and maintenance tasks. In contrast, graduates from general academic pathways often require longer adaptation periods and closer supervision, increasing the likelihood of operational deviations and maintenance-related errors during the early stages of employment [14]-[16].

F. Research Gap

This research addresses this gap by positioning human error as a central concern in agricultural manufacturing systems. By integrating human error considerations into a structured framework based on the 4M model, the study aims to support more reliable, preventive, and sustainable manufacturing processes in agriculture-based industries. This research aims to identify and analyze sources of human error in agricultural manufacturing operations and maintenance, examine their interactions with machinery condition, material variability, and production methods, and propose design- and maintenance-oriented strategies that shift management practices from corrective to preventive approaches, thereby improving reliability, safety, and sustainability in starch-based and similar agricultural industries through a 4M-based framework that systematically integrates human capability (Man), maintainable and error-tolerant equipment (Machine), robustness to raw material variability (Material), and standardized preventive methods with early error detection (Method), while acknowledging that validation is primarily limited to starch processing systems and influenced by organizational, cultural, and resource constraints.

II. Problem Statement

A. System Platform

Agricultural manufacturing systems, especially those that use traditional processing methods, operate under conditions in which human judgment and manual intervention dominate daily activities. Over time, repeated exposure to the same processes normalizes deviations, shortcuts, and minor mistakes [17]. Maintenance actions often rely on experience rather than documented procedures, and workers rarely record or analyze errors such as incomplete inspections, improper adjustments, or delayed repairs [18]. Human error in these systems typically results not from negligence but from systemic conditions such as time pressure during harvest seasons, fatigue from long working hours, limited training, and inadequate machine design. These factors increase the likelihood of errors during operation and maintenance, particularly in processes such as drying, milling, separation, and material transfer.

B. Equipment Platform

In many agricultural factories, maintenance remains largely corrective. Equipment is repaired only after failure, often under urgent conditions that increase the risk of error. Without structured error detection or early-warning mechanisms, latent errors remain unnoticed. Over time, these errors lead to equipment breakdowns, safety incidents, or quality nonconformities that disrupt production and increase costs [19]-[21]. In addition, growing regulatory requirements for food safety, traceability, and environmental performance further pressure agricultural manufacturing systems [22]. Human errors during cleaning, calibration, or maintenance can cause contamination, excessive energy use, or noncompliance with standards. Despite these challenges, few traditional factories have frameworks that explicitly link human error with maintenance engineering and process management. Therefore,

an integrated approach is needed that recognizes human error as an inherent part of agricultural manufacturing and manages it systematically through design, training, maintenance planning, and process standardization.

III. Research Background

In Thailand, educational pathways differ significantly in how well they align with labor market needs, particularly in practical skills and workforce readiness. Technical and Vocational Education and Training (TVET) programs are specifically designed to develop hands-on competencies, technical skills, and industry-relevant knowledge, especially at the upper secondary and post-secondary levels [23]-[24]. About one-third of Thai upper secondary students are enrolled in vocational tracks, and vocational programs also account for a substantial share of post-secondary enrolment, reflecting TVET's important role in workforce preparation [25]. Evidence indicates that vocational education in Thailand is associated with more favorable employment outcomes compared with general academic education at the same level. Graduates from vocational and technical programs tend to have higher employment rates, improved job matching, and a lower likelihood of working in informal or low-skilled occupations than graduates from general academic tracks [26].

Fig. 2 shows how operator overconfidence (10 years of experience) during welding can directly affect finished-part quality, leading to a *Short Trim Line* defect [27]. Process improvement can be achieved through proper training and retraining, even for skilled workers who have graduated from vocational tracks and possess strong operational competencies. Although these workers have substantial experience, long-term involvement in the same operation may lead to overconfidence and reduced adherence to standard procedures.

In this case, targeted retraining and upskilling programs can help reinforce best practices, improve process discipline, and reduce defect rates.

Graduates from vocational and technical education pathways in Thailand consistently align more closely with labor market requirements in manufacturing sectors than those from general academic education at the same level. Vocational education emphasizes practical training, machine operation, and real-world problem-solving, which directly supports employment in industrial and agricultural manufacturing environments. In contrast, general academic pathways prioritize theoretical knowledge and preparation for higher education, often resulting in weaker job–specific skills for operational roles. These differences explain why technical and vocational graduates are more frequently employed in manufacturing positions, experience lower informality risk, and demonstrate higher operational efficiency in practice-oriented industries.

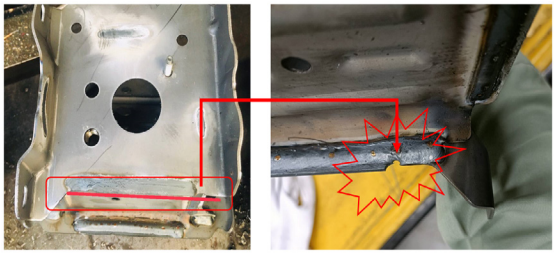

Fig. 2. Defect found during the task – welding process [27]

Table I presents data on enrollment and graduation among Thai Technical and Vocational Education and Training (TVET) students. The statistics indicate that Thailand's TVET system remains a major source of industrial labor, particularly for production and maintenance roles. On average, more than 170,000 students are admitted annually to the vocational certificate level and over 129,000 to the higher vocational diploma level, for a total of almost 300,000 students per year. Meanwhile, graduates from the vocational certificate level exceed 126,000 per year, while approximately 117,000 graduate from the higher vocational diploma level, for a combined output of about 240,000 graduates per year. This sustained supply highlights TVET institutions' critical role in supporting labor-intensive and error-sensitive industries such as automotive manufacturing and agricultural processing. Because TVET education is hands-on, students learn through workshop-based training, direct interaction with industrial equipment, and exposure to real operational constraints. As a result, graduates tend to develop stronger procedural discipline, practical problem-solving ability, and familiarity with standard operating procedures earlier than those following general academic education pathways, which primarily emphasize theoretical knowledge. [28].

Moreover, vocational education has been shown to increase the probability of employment in industrial and manufacturing sectors, where practical skills and operational competence are critical. These findings suggest that graduates of technical or vocational schools are often better prepared for practical manufacturing tasks than those from general academic pathways. This distinction matters especially in agricultural manufacturing, where daily operations depend heavily on equipment handling, routine maintenance, and process adjustment, and where stronger technical training can improve efficiency and reduce human error. Table II presents a comparative overview of education pathways in Thailand and their employment outcomes, emphasizing workforce readiness for manufacturing and agricultural industries.

TABLE I
ENROLLMENT AND GRADUATION STATISTICS FOR THAI TECHNICAL AND VOCATIONAL EDUCATION AND TRAINING (TVET) [28]

Academic Year	New Admissions (Vocational Certificate)	Graduates (Vocational Certificate)	New Admissions (Higher Vocational Diploma)	Graduates (Higher Vocational Diploma)
2017	165,766	80,875	112,229	87,858
2018	72,202	124,732	51,048	122,771
2019	N/A	130,116	N/A	118,489
2020	166,557	140,755	116,126	122,585
2021	229,380	148,351	166,310	141,981
2022	218,798	106,781	160,928	95,976
2023	213,652	155,873	168,746	130,054
Average	**177,652**	**126,783**	**129,231**	**117,102**

TABLE II
COMPARISON OF EDUCATION LEVELS AND EMPLOYMENT OUTCOMES IN THAILAND

Education Level	Training Focus	Practical Skill Intensity	Employment Rate (Relative)	Manufacturing Employment Likelihood	Job–Skill Match	Informality Risk
Lower Secondary (Junior High School)	Basic general education	Very Low	Low	Very Low	Poor	High
Upper Secondary (General Academic)	Academic knowledge	Low	Moderate	Low	Moderate–Poor	Moderate–High
Upper Secondary (Vocational/Technical)	Hands-on technical skills	High	High	High	Good	Low–Moderate
Post-Secondary Vocational Diploma (TVET)	Advanced technical skills	Very High	Very High	Very High	Very Good	Low
University Degree (General)	Theoretical knowledge	Moderate	High	Moderate	Moderate	Low
University Degree (Engineering)	Applied technical theory	High	High	High	Good	Low

A. House of Quality (HoQ) Framework

House of Quality (HoQ) framework has been created to support the research on human error prevention in agricultural and starch-based manufacturing, where:

Customer = Manufacturer or business owner

Customer Requirements (CRs) = Expectations related to smooth operations and effective maintenance performance

Technical Characteristics (Roof/Specifications) = Specific worker skills and competencies required to prevent human error

We obtained all data used in the House of Quality (HoQ) framework through structured interviews with experienced business owners in the agricultural and starch-based manufacturing sectors. We derived the customer requirements, technical skills, importance ratings, and relationship levels directly from their expert insights and operational experience.

We collected the data used in the House of Quality (HoQ) framework through structured interviews with experienced business owners in the agricultural and starch-based manufacturing sectors. We systematically derived all Customer Requirements (CR1-CR6) (Table III), Technical Skills (TS1-TS7) (Table IV), importance ratings, and relationship levels (Table V) from their expert knowledge and operational experience.

Interviews focused on operational stability and maintenance effectiveness to identify Customer Requirements and their corresponding 1-5 importance ratings. The team synthesized technical skills from expert input on the competencies needed to prevent operational errors and equipment failures. Experts

determined the relationship levels within the HoQ matrix through interviews, in which participants assessed how each technical skill supports each customer requirement.

Because human error arises from interactions among workforce capability, equipment condition, material variability, and operational methods, a structured tool is needed to translate managerial requirements into technical and organizational actions. Traditional problem-solving approaches in agricultural manufacturing often address errors only after failures occur, offering limited support for preventive decision-making. Therefore, this study adopts the Quality Function Deployment (QFD) approach, with the House of Quality (HoQ) serving as a central analytical framework to explicitly link manufacturer and business-owner requirements—such as stable production, reliable maintenance, and reduced operational risk—to specific workforce skills, machine design considerations, and standardized procedures aimed at preventing human error.

B. Customer Voice (Manufacturer and Business Owner Requirements)

From the perspective of manufacturers and business owners, operational success in agricultural manufacturing depends strongly on workforce capability. Their primary requirements focus on stable production, controlled maintenance, and reduced risk of human error. These requirements reflect organizational and business priorities rather than individual worker preferences, aligning directly with the House of Quality (HoQ) concept, where the "customer" represents the manufacturer or business owner. From this perspective, key requirements include stable and continuous production, reduced unplanned machine downtime, consistent product quality, lower maintenance and operating costs, compliance with safety and food standards, efficient use of energy and materials, and predictable, preventive maintenance performance, all of which are essential for reducing human error and improving the overall reliability and sustainability of agricultural manufacturing systems.

C. Technical Characteristics (Worker Skills and Specifications)

To meet these requirements, workers must have specific technical characteristics. These characteristics represent measurable skills, competencies, or qualifications that directly influence error prevention: technical skill in machine setup and adjustment, ability to interpret operating parameters and process conditions, preventive maintenance knowledge, equipment inspection and fault-detection capability, understanding of material variability and process sensitivity, ability to follow standardized work procedures, safety and hygiene awareness, problem-solving and root cause analysis skill, and documentation and reporting discipline.

IV. Relationship Strength (Typical HoQ Interpretation)

This relationship mapping highlights which worker competencies most impact human error prevention. The roof of the HoQ (Fig. 3) (Correlation between Skills) illustrates interrelationships among worker skills:

- Preventive maintenance skill strongly supports fault detection ability
- Standardized work compliance reduces dependency on individual experience
- Process understanding enhances correct machine setup and material handling
- Problem-solving skills strengthen preventive decision-making

Positive correlations indicate that developing technical-school-level competencies can improve multiple performance dimensions simultaneously.

- Strong relationship (●)
  Preventive maintenance knowledge ↔ Reduced downtimeFault detection skill ↔ Stable production
- Moderate relationship (○)
  Standardized procedures ↔ Product quality Safety awareness ↔ Compliance
- Weak relationship (△)
  Documentation skill ↔ Energy efficiency

For interpretation and linking to human error, the HoQ demonstrates that human error in agricultural manufacturing is not random, but closely linked to skill gaps and unclear task requirements. Workers with technical and vocational training—especially those from technical colleges—are more likely to possess structured skills aligned with preventive maintenance, standardized procedures, and early error detection.

In contrast, workers without technical backgrounds tend to rely on experience-based judgment, increasing the likelihood that errors remain unnoticed until failure occurs. By using this HoQ, manufacturers can translate business expectations into concrete workforce skill requirements, supporting decisions on recruitment, training, and collaboration with technical education institutions.

A. Case Study: House of Quality (HoQ) for Human Error Prevention in Thailand's Starch, Sago, and Cassava Manufacturing Industries

This House of Quality translates manufacturer and business owner requirements into worker skills and technical competencies required to prevent human error in agricultural manufacturing. The framework is aligned with Thai technical and vocational education

pathways and supports preventive maintenance engineering.

For *'Roof of the House (Skill Correlation)'*, key specifications are considered as follows:

• Preventive maintenance skill (TS2) strongly supports fault detection and reduced downtime
Process understanding (TS3) improves machine setup accuracy (TS1)

• SOP compliance (TS5) reduces reliance on experience-based judgment

• Safety awareness (TS6) strengthens regulatory compliance and risk prevention

Positive correlations indicate that technical education produces multi-skill benefits for error prevention.

TABLE III
CUSTOMER REQUIREMENTS (MANUFACTURER / BUSINESS OWNER)

Co	Customer Requirements	Description	Importance(1-5)
CR1	Stable production	Continuous operation without interruption	5
CR2	Reduced machine downtime	Minimized unplanned breakdowns	5
CR3	Consistent product quality	Uniform moisture, granule size, and cleanliness	4
CR4	Lower maintenance cost	Reduced repair and replacement expenses	4
CR5	Safety and regulatory compliance	GMP, HACCP, Thai food safety laws	5
CR6	Energy efficiency	Reduced fuel and electricity consumption	3

TABLE IV
TECHNICAL CHARACTERISTICS (WORKER SKILLS / SPECIFICATIONS)

Code	Worker Skill / Specification	Description	Education Pathway in Thailand
TS1	Machine setup & adjustment	Correct setting of dryers, mills, and separators	Technical College / Vocational Certificate
TS2	Preventive maintenance skill	Inspection, lubrication, and early fault detection	Technical College / Diploma
TS3	Process parameter interpretation	Temperature, vibration, and moisture control	Technical College / Diploma
TS4	Material handling knowledge	Managing cassava/starch variability	Vocational / On-the-job training
TS5	Standard Operating Procedures (SOPs) compliance	Ability to follow standard procedures	Vocational emphasis
TS6	Safety & hygiene awareness	Food safety and machine safety	Vocational / University
TS7	Problem-solving skill	Root cause analysis of defects	Diploma / University

TABLE V
HOUSE OF QUALITY RELATIONSHIP MATRIX

Customer Requirement	TS1	TS2	TS3	TS5	TS6
Stable production (CR1)	●	●	●	○	△
Reduced downtime (CR2)	○	●	○	○	△
Product quality (CR3)	●	○	●	●	○
Maintenance cost (CR4)	○	●	○	△	△
Safety & compliance (CR5)	△	○	○	●	●
Energy efficiency (CR6)	○	○	●	△	△

(Relationship: Strong = ●, Moderate = ○, Weak = △)

Quality Function Deployment

Project title: Linking Stakeholder Needs to Worker Competencies

Project leader: SR

Date: 11-Sep-25

Correlation:

+	●	–
Positive	No correlation	Negative

Relationships:

9	5	1	
Strong	Moderate	Weak	None

1: low, 5: high

	Customer importance rating	Customer requirements - (What's) ↓	Machine setup & adjustment	Preventive maintenance skill	Process parameter interpretation	Material handling knowledge	Standard Operating Procedures (SOPs) compliance	Safety & hygiene awareness	Problem-solving skill	Weighted score
		Desired direction of improvement (↑,0,↓)	↑	↑	↑	↑	↑	↑	↑	
		Functional requirements (How's) →								
1	5	Stable production	9	9	9	9	5	1	9	255
2	5	Reduced machine downtime	5	9	5	5	5	1	9	195
3	4	Consistent product quality	9	5	9	1	9	5	5	172
4	4	Lower maintenance cost	5	9	5	1	1	1	5	108
5	5	Safety and regulatory compliance	1	5	5	1	9	9	1	155
6	3	Energy efficiency	5	5	9	1	1	1	1	69
		Technical importance score	146	186	178	86	138	82	138	954
		Importance %	15%	19%	19%	9%	14%	9%	14%	100%
		Priorities rank	3	1	2	6	4	7	4	

Fig. 3. House of Quality – linking stakeholder needs to worker competencies

B. Interpretation and Link to Thai Education Pathways

The HoQ (Fig. 3) results demonstrate that human error in starch-based manufacturing is strongly linked to workforce skill structure rather than individual negligence. Skills that most affect production stability and maintenance reliability—such as preventive maintenance, machine setup, and process interpretation—are core competencies emphasized in Thai technical and vocational education systems. Operators graduating from technical colleges and vocational institutions are typically trained through hands-on workshops, equipment-based learning, and maintenance-focused curricula. This preparation supports early error detection and preventive behavior. In contrast, workers from general education pathways often rely on experience-based decision-making, increasing the likelihood that errors remain unnoticed until failure occurs.

V. Discussion

A. Automotive Manufacturing Focus

In traditional automotive manufacturing factories [Mr. Chatchai Vorathanawat [Managing Director, Thai Saeng Charoen Service Co., Ltd. (TSS)], production systems rely heavily on manual operation, routine inspection, and maintenance activities performed by shop-floor technicians. These environments typically involve aging equipment, partial automation, and high production pressure, which together increase the likelihood of human error during machine setup, adjustment, and maintenance. As a result, workforce capability becomes a critical determinant of operational reliability, equipment availability, and product quality. In the Thai context, graduates from vocational and technical education pathways align more closely with the practical demands of automotive manufacturing than graduates from general academic education at the same level. Technical and vocational programs emphasize hands-on training, machine operation, preventive maintenance practices, and fault diagnosis. These competencies enable technicians to recognize abnormal conditions—such as vibration, noise, temperature deviation, or tool wear—early, reducing the likelihood that minor errors escalate into major breakdowns or quality defects. In contrast, general academic pathways primarily focus on theoretical knowledge and preparation for higher education, which may limit graduates' readiness for maintenance-intensive shop-floor roles.

B. A Maintenance Engineering Perspective

From *a maintenance engineering perspective*, human error in automotive factories often stems not from negligence but from insufficient technical grounding, unclear procedures, or limited experience with real equipment. Errors such as incorrect parameter settings, incomplete inspections, or delayed maintenance actions can remain unnoticed until failure occurs. Technically trained personnel are better equipped to follow standard operating procedures, perform systematic inspections, and apply preventive maintenance principles, thereby supporting a shift from corrective to preventive maintenance strategies [29].

C. Framework of Quality Function Deployment (QFD) and the House of Quality (HoQ)

Within the *Quality Function Deployment (QFD) and House of Quality (HoQ) framework,* manufacturers' requirements—such as stable production, reduced downtime, consistent quality, and controlled maintenance costs—can be interpreted as the "voice of the customer." These requirements translate into technical characteristics, which in this case correspond to workforce skills and competencies. Preventive maintenance capability, accurate machine setup, process understanding, and compliance with Standard Operating Procedures (SOPs) emerge as critical technical characteristics that directly influence human error prevention. Accordingly, the HoQ analysis supports the view that vocational and technical education pathways play a crucial role in meeting the operational needs of traditional automotive manufacturing. By aligning workforce development with manufacturer requirements, these pathways improve maintenance performance, reduce human error, and enhance the long-term sustainability of automotive production systems.

V. Some Common Mistakes

A. Automotive Industry – Examples of Human Error and Operational Failures

ISSUE I: Automotive Acceleration Problems and Recalls

One of the most widely cited cases involving vehicle defects and human interaction is the Toyota unintended acceleration incidents from 2009-2011, where floor mat placement and accelerator pedal sticking led to numerous reported accidents and safety recalls. The problem was initially attributed to driver error (e.g., pedal misapplication), highlighting how unclear procedures or failures to follow test/check protocols contributed to serious outcomes that required mass recalls and repair work [30].

ISSUE II: General Motors Ignition Switch Defect

In the early 2010s, General Motors recalled millions of vehicles because a faulty ignition switch could shut off the engine while driving, leading to crashes and fatalities. Investigations pointed to design and quality-control errors, some tied to inadequate verification of assembly specifications and testing procedures. This type of systemic error can be exacerbated when workers or supervisors with limited technical training misinterpret test results or fail to enforce quality checks [31].

B. Agricultural Industry – Examples of Operational and Safety Errors

ISSUE I: Tractor Overturn and Steering Instability

Research on tractor accidents shows that steering instability is a key factor in overturn incidents, especially on uneven terrain. While not purely education-dependent, avoiding such accidents often requires skilled training in machine operation and an understanding of vehicle dynamics—skills more likely found in vocationally trained operators [32].

ISSUE II: Human Errors in Manual Agricultural Tasks

Agricultural manufacturing industries transform raw agricultural products into materials suitable for food, industrial, and consumer applications. Among these industries, starch-based manufacturing represents a critical link between agriculture and downstream production, supplying inputs for food, pharmaceuticals, packaging, and bio-based products. While technological advances have increased efficiency and automation in modern plants, much of agricultural manufacturing—particularly starch, sago, and cassava processing—still relies on traditional factories with manual operations and human-centered decision-making.

In these environments, humans remain central to daily production and maintenance. Operators and technicians handle machine setup, material handling, inspection, adjustment, and repair, making human error a major factor affecting process stability, product quality, equipment reliability, and safety. Prior research shows that improvements in agricultural machinery management depend not only on advanced technology but also on operator skills, maintenance practices, and the quality of operational decision-making, all of which directly influence efficiency, machine downtime, and error occurrence [33].

Unlike discrete manufacturing sectors, agricultural processing deals with biological raw materials that vary in moisture content, particle size, and contamination levels. This variability increases process complexity and places additional demands on workers. Consequently, small human errors—such as incorrect machine settings, delayed maintenance,

unnoticed vibration, or improper cleaning—can propagate through the production chain, leading to quality losses, energy waste, and equipment damage. In traditional factories, people often treat these errors as isolated incidents rather than signs of underlying systemic weaknesses.

ISSUE III: Grain Entrapment and Safety Oversights

Grain entrapment, where workers are suffocated in storage bins, continues to be a major hazard in agricultural facilities worldwide. Most documented entrapments occur not because of machine failure but because workers lack training in safe grain handling, confined-space entry procedures, and emergency protocols—areas where vocational and technical education could build stronger prevention skills [34].

TABLE VI
SUMMARY OF HUMAN ERRORS IN RELATION TO EDUCATIONAL PATHWAYS

Industry	Example Error	Likely Skill Gap	Link to Education
Automotive	Toyota's unintended acceleration issues	Misapplication of test/inspection protocols; procedural gaps	Vocational training would improve hands-on diagnostic and compliance skills
Automotive	GM ignition switch recall	Inadequate verification & quality control during assembly	Technical training enhances detailed quality inspection
Agricultural	Tractor overturning	Lack of operation skills and understanding of machine behavior	Vocational schooling offers targeted machinery operation training
Agricultural	Rice transplanting errors	Multitask management and procedural oversight	Structured on-farm safety and process training improves outcomes
Agricultural	Grain entrapment	Confined-space awareness and safety procedures	Formal safety training reduces errors that may result in loss of life

Table VI summarizes the examples of human error in both industries, the associated skill gaps, and their links to education and training. A key consideration is that human error in both the automotive and agricultural sectors is not just about individual mistakes—it often reflects gaps in practical skills, task-specific training, and procedural understanding. Workers from vocational and technical education pathways generally show stronger preparation for these hands-on challenges, whereas those from general academic (12-year or bachelor's) pathways may be less practiced in real-world operations and maintenance tasks, increasing the likelihood that errors go unnoticed or uncorrected until serious consequences occur.

C. Why These Errors Relate to Educational Pathways

1) Vocational/Technical Education

This emphasizes hands-on equipment operation, recognition of abnormal conditions, and preventive maintenance. Structured training in problem-solving, SOP adherence, and early fault detection are key to reducing human error. Graduates are better prepared for repetitive, machine-intensive tasks and complex procedures that require applied skills.

2) General Academic (Grade 12 / Bachelor)

Focuses more on *theoretical knowledge* and broad conceptual education rather than applied shop-floor skills. Workers may understand principles but lack training in specific procedures, troubleshooting steps, or real-world risk indicators, leading to more unnoticed human errors during routine work.

VI. RESULTS AND DISCUSSION

This section discusses *'Human Error, Skill Gaps, and Education Pathways in Thailand.'* Agricultural and automotive manufacturing rely heavily on manual operations, making human error a key factor in process instability and equipment failure. Education shapes workforce capability: TVET programs emphasize hands-on skills and problem-solving, while general academic paths focus on theory. Vocational graduates exhibit higher employment rates, better job–skill alignment, and greater engagement in manufacturing. Using the 4M framework with QFD and HoQ, this study links manufacturer requirements to workforce competencies, promoting preventive practices and enhancing reliability, safety, and sustainability.

A. Automotive Manufacturing Context

Thailand's automotive industry operates under stringent quality and safety standards, where errors in machine setup, torque application, preventive maintenance, and process monitoring can lead to recalls, downtime, or safety incidents. Studies and industry reports indicate that maintenance-related errors—such as improper lubrication, delayed inspection, or misinterpretation of sensor signals—often stem from insufficient hands-on training rather than a lack of theoretical knowledge [35]-[36]. TVET and engineering graduates typically possess stronger competencies in *maintenance engineering, root cause analysis, and procedural compliance,* enabling them to detect early signs of failure and respond preventively. Conversely, general academic graduates

assigned to operational roles may struggle with real-time decision-making in high-pressure environments, increasing dependency on trial-and-error learning.

B. Agricultural and Starch-Based Manufacturing Context

In agricultural manufacturing—particularly in starch, sago, and cassava processing—the risk of human error is amplified by material variability and aging equipment [37]-[38]. Operators must continuously adjust process parameters such as temperature, moisture content, and separation efficiency. Errors such as incorrect dryer settings, incomplete cleaning, or overlooked vibration often originate from inadequate process understanding or weak SOP discipline. Technical and vocational graduates in Thailand are generally trained to handle such variability through repeated practice and on-site training modules. Their stronger alignment with operational tasks supports more stable production, fewer quality deviations, and reduced unplanned downtime, meeting the manufacturer's core requirements identified in the HoQ framework.

VII. Importance Scale for Human Error Prevention

The importance score reflects the severity of human error's impact on product quality, production continuity, safety, and system reliability, considering both the likelihood of failure and the likelihood of occurrence. Table VIII defines the five importance levels used to assess the impact of human error in manufacturing. In OEM automotive manufacturing, high-importance errors linked to habitual operator behaviors are typically associated with long-term familiarity, reduced vigilance, and normalization of abnormal conditions, which increase failure rates despite stable equipment. Integrating procedural controls, digital monitoring, and behavioral interventions improves MTTF and system reliability, supporting a shift from corrective to preventive manufacturing practices [39]-[42]. Table IX presents a reliability-based interpretation of the importance levels using failure rates and 24-hour reliability values.

A. Situation: Human Error in OEM Automotive Manufacturing Due to Work Habituation

Table VII illustrates that human error driven by routine normalization and reduced caution significantly impacts reliability, a pattern equally evident in OEM automotive manufacturing. These findings emphasize the need for preventive approaches—including standardized checks, parameter monitoring, job rotation, refresher training, and skill-based workforce design—rather than relying on experience alone to prevent quality degradation caused by human habituation. In OEM automotive manufacturing, especially on mature production lines with long-serving operators, human error often stems not from a lack of skill but from overfamiliarity with routine tasks. Similar failures occur when insufficient drying temperature, excessive temperature, or inadequate duration repeatedly occur due to human error [43]-[44]. Automotive production lines experience comparable issues in processes such as heat treatment, welding, painting, molding, and assembly torque application [45].

TABLE VII
HUMAN ERROR–RELATED CAUSES AFFECTING SUBSYSTEM RELIABILITY

No.	Automotive Failure Situation	Typical Process	Human Error Cause	Importance (1–5)	Priority Rank	MTTF (hr)	MTTR (hr)	MTBF (hr)	Failure Rate (1/hr)	Reliability (24 hr)	Preventive Guideline
1	Incorrect process temperature (too low)	Heat treatment, paint curing	Operator skips parameter check due to routine	5	High	355	5	360	0.0028	0.935	Mandatory digital setpoint confirmation and alarms
2	Incorrect process temperature (too high)	Welding, curing	Overcorrection based on past defects	5	High	719	1	720	0.0014	0.967	SPC-based limits with real-time feedback
3	Inadequate process duration	Bonding, curing	Time-saving shortcuts under pressure	4	High	60	0.2	60	0.0167	0.67	Automated timer interlock (no manual override)
4	Excessive process duration	Welding, coating	Habitual compensation without data	3	Medium	719	1	720	0.0014	0.967	Standard cycle enforcement via PLC
5	Improper material thickness / quantity	Coating, molding	Visual judgment replaces measurement	4	High	90	0.1	90	0.0111	0.766	Poka-yoke gauges and fixture control
6	Missed inspection steps	Assembly, in-process QC	"Nothing usually fails here" mindset	5	High	72	0.1	72	0.0139	0.716	Checklist sign-off with random audits
7	Environmental contamination	Painting, clean assembly	Failure to close covers/screens	5	Very High	24	0.03	24	0.0417	0.367	Visual status indicators + interlocks

TABLE VII
HUMAN ERROR–RELATED CAUSES AFFECTING SUBSYSTEM RELIABILITY

No.	Automotive Failure Situation	Typical Process	Human Error Cause	Importance (1–5)	Priority Rank	MTTF (hr)	MTTR (hr)	MTBF (hr)	Failure Rate (1/hr)	Reliability (24 hr)	Preventive Guideline
8	Ignored abnormal noise / vibration	Presses, conveyors	Habituation to abnormal conditions	4	High	72	0.1	72	0.0139	0.716	Early-warning dashboards and reporting
9	Repetitive minor defects	Final assembly	Reduced attention due to repetition	3	Medium	90	0.1	90	0.0111	0.766	Job rotation and fatigue management
10	Reactive maintenance behavior	All machinery	Experience replaces condition monitoring	4	High	360	5	360	0.0028	0.935	Condition-based maintenance indicators

TABLE VIII
IMPORTANCE SCALE DEFINITION FOR HUMAN ERROR PREVENTION

Score	Importance Level	Definition	Typical Impact in Manufacturing
5	Critical	Errors that can immediately cause severe quality defects, safety hazards, regulatory non-compliance, or major production shutdowns	Line stoppage, safety incidents, recalls, major equipment damage
4	High	Errors that significantly degrade product quality or system reliability and require corrective action, but do not cause immediate shutdown	Rework, scrap increase, frequent downtime
3	Moderate	Errors that affect process stability or efficiency but are detectable and correctable within normal operations	Minor defects, reduced throughput
2	Low	Errors with limited impact on quality or performance and minimal operational disruption	Small efficiency loss, cosmetic defects
1	Very Low	Errors with negligible impact and no noticeable effect on system performance or safety	No measurable impact

TABLE IX
RELIABILITY-BASED INTERPRETATION OF IMPORTANCE

Importance	Failure Rate (λ, 1/h)	24-h Reliability	Interpretation
5	≥ 0.0050	≤ 0.88	Unacceptable risk; immediate preventive action required
4	0.0030-0.0049	0.88-0.92	High risk; prioritized mitigation needed
3	0.0015-0.0029	0.92-0.95	Manageable risk; monitoring and training recommended
2	0.0005-0.0014	0.95-0.98	Low risk; routine control sufficient
1	< 0.0005	> 0.98	Minimal risk; no additional action required

TABLE X
SUMMARY OF HUMAN ERRORS IN RELATION TO EDUCATIONAL PATHWAYS

Industry	Common Human Error Type	Underlying Skill Gap	Typical Education Background	Relative Error Risk
Automotive	Incorrect machine setup or torque application	Practical machine calibration skills	General Upper Secondary / Non-engineering Bachelor	High
Automotive	Delayed fault detection	Preventive maintenance knowledge	General Academic	Moderate–High
Automotive	SOP deviation during assembly	Procedural discipline and hands-on training	Vocational / TVET	Low
Agricultural (Starch/Cassava)	Incorrect dryer or separator settings	Process parameter interpretation	General Academic	High
Agricultural (Starch/Cassava)	Incomplete cleaning and sanitation	SOP compliance and hygiene training	Vocational / TVET	Low
Agricultural (Starch/Cassava)	Unnoticed vibration or wear	Early fault recognition	Technical Diploma / Engineering	Very Low

C. Summary of Human Errors in Relation to Educational Pathways

Table X shows that human errors differ by industry and are strongly related to skill gaps and educational background. In the automotive industry, tasks such as machine setup and torque application have a high risk of error when operators lack practical calibration skills. Delayed fault detection also shows moderate-to-high risk, indicating limited knowledge of preventive maintenance. In contrast, standard Operating Procedure (SOP) deviations during assembly carry lower risk, suggesting that vocational and TVET training supports strong procedural compliance.

In the agricultural (starch/cassava) industry, incorrect dryer or separator settings are high-risk errors, mainly because workers struggle to understand process parameters. However, cleaning and sanitation errors are less frequent when workers receive proper SOP and hygiene training. Early detection of machine vibration or wear poses very low risk when workers with technical or engineering backgrounds handle it. Overall, the results indicate that matching job tasks with appropriate skills and training can significantly reduce human error.

VIII. Conclusion

From a QFD/HoQ perspective, manufacturers and business owners represent the "customer," prioritizing stable production, preventive maintenance, safety compliance, and cost control. Therefore, human error prevention is not an individual-level issue but a system-level requirement that must translate into technical characteristics, particularly workforce skills and education pathways.

Comparative evidence from Thailand's automotive and agricultural sectors supports including worker skill specifications—such as preventive maintenance capability, SOP compliance, and process interpretation—as critical "HOWs" in the House of Quality. Aligning recruitment and training strategies with vocational and technical education pathways directly reduces human error and enhances long-term operational sustainability. This evidence reinforces the view that technical and vocational education pathways function as enabling specifications within the HoQ structure. By systematically linking manufacturer requirements (WHATs) to workforce competencies (HOWs), organizations can reduce reliance on corrective actions and move toward preventive, error-resilient manufacturing systems.

Acknowledgment

The authors sincerely thank the Industrial Engineering Laboratory, School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology (SIIT), Thammasat University, for providing the research instruments, facilities, and valuable technical assistance that significantly contributed to completing this paper. The first author also gratefully acknowledges the financial support provided by the Excellent Thai Student (ETS) Scholarship, awarded by Sirindhorn International Institute of Technology, Thammasat University. The authors thank Mr. Vacharatorn Kitaphanich, President and Member of the Executive Board and Director of Somboon Advance Technology Public Company Limited, for sharing his extensive experience in commercial operations, business development, and research and development in the automotive and advanced manufacturing sectors. His industry insights were instrumental in evaluating the advantages and limitations of EV tri-wheel vehicle development. The authors gratefully acknowledge Mr. Wichayut Kitaphanich, Business Development Manager of Somboon Advance Technology Public Company Limited, for his valuable technical support and professional collaboration on EC tri-motor vehicle systems, which substantially contributed to the successful completion of this research study. The authors also sincerely acknowledge Mr. Supavich Vongvivat, Founder of Smiling Mad Dog Co., Ltd., for his valuable contributions from a design and business development perspective. His insights into human error considerations and customer typologies are particularly important for new-to-trend and next-generation business development, and they provide a meaningful foundation for further studies in the beverage and agricultural-based raw material industries.

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