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A TRIZ-Supported Concept and Protocol Development for Roof Tile Transportation and Inspection Systems

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Abstract: Currently, the use of manual labour in the transportation and inspection systems of leading roof tile manufacturing companies in Indonesia is still prevalent. Manual labour is usually labour-intensive, has higher risks of musculoskeletal disorders, and produces frequent occurrences of errors and losses. Furthermore, the current studies of suitable concepts and test protocols for roof tile transportation at the manufacturing stage as well as their inspection systems are not practicable in Indonesia. There is also no study that has used the theory of inventive problem-solving (TRIZ) in the development of concepts and protocols for roof tile transportation and inspection systems. Using TRIZ as a supporting tool, this study investigated the development of a transportation system to be employed during the manufacturing of the roof tile and a test protocol for their usability in Indonesian companies to overcome this concern. The study included screening and scoring concepts and usability test protocols identified from the existing literature, with the support of TRIZ tools such as the engineering contradiction, contradiction matrix, and inventive principles. Thus, the finalised concept comprised a belt conveyor system (Inventive Principle 20: Continuity of Useful Action) with a flipping mechanism for transportation and a vision-based camera for inspection. Results of the study showed that the concept excelled in cost, durability, reliability, versatility, low risk to the product, efficiency, and safety. The t-test protocol (Inventive Principle 23: Feedback) was selected based on the results due to its versatility in testing efficiency, reliability, and productivity. It was concluded that this concept has the potential to alleviate roof tile workers of physical work and reduce the prevalence of musculoskeletal disorders.

Keywords: roof tile; transportation; inspection; conceptualisation; protocol; usability; manufacturing

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1. Introduction

Roof tile manufacturing industries in Indonesia are highly oriented towards manual labour, which requires operators to carry and transport heavy tile stacks over their backs and shoulders. Similarly, the brick and plastic manufacturing industries require physical labour. Thus, workers are exposed to severe musculoskeletal disorders (MSDs), such as upper limb disorders and back pain [1–3]. If the activities are repeated for a prolonged period, serious MSDs may occur in the production workforce. Continual lifting or prolonged repetitive motions are some of the causes that may lead to MSDs [4]. Other injuries, such as muscle sprains, strains, and ligament tears, can also occur [5]. Hence, there is a need to increase the productivity of the roof tile transportation process while reducing its reliance on manual labour. Eventually, the decrease in reliance on manual labour in this industry would reduce safety and MSD risks among the workers.

Studies have been conducted to increase automated processes in the manufacturing industry to reduce manual labour and increase productivity [6–8]. For example, Florescu and Barabas [6] analysed a technical and economic performance of a flexible manufacturing system using modelling and simulation techniques. Likewise, Liu, et al. [9] emphasised the need to develop advanced technologies and reconfigurable machine tools (RMT) with a high degree of flexibility integrated into manufacturing systems. Moreover, the study reported the need to develop protocols and numerical simulation models on production lines. In Table 1, the summary of the key findings on MSDs from past studies is depicted. Based on the findings, outdated manufacturing processes often still rely on large amounts of manual labour, from which the workers of these manufacturing processes can eventually develop MSDs. The studies on manufacturing firms discovered that manual workers often suffer from certain types of MSDs impacting the neck, lower back, knees, and upper back and limbs. The MSDs occur due to awkward postures during material handling and repetitive work without rest [2,5,10]. Furthermore, researchers discovered that implementing job rotation might reduce physical ergonomic risks [11].

Table 1. Summary of key findings of past studies on MSDs.

Key Findings	Ref.
- Most workers suffered from MSDs in the lower back, knees, and upper back regions. - Occurred due to awkward postures during manual material handling activities (lifting).	[5]
- Upper limb and shoulder-based MSDs were prevalent among manual workers in manufacturing firms. - Repetitive work and lack of rest breaks were risk factors influencing the prevalence of MSDs. - MSDs have a significant negative impact on the general health of workers.	[10]
- Upper limb-based MSDs were related to manual handling and work repetitiveness. - Neck, shoulder, and upper back-based MSDs were also prevalent. - Prevalence of MSDs can be reduced by improving the working environment, reducing risk factors, and replanning work organisation.	[2]
- Implementation of job rotation can reduce physical ergonomic risks.	[11]

The summary of key findings on transportation systems from previous studies is tabulated in Table 2. With regard to material transportation systems, a Table Top Chain (TTC) conveyor system was proposed by Butt and Jedi [12] with the DFMA (Design for Manufacture and Assembly) approach. This approach has led to an improvement in cost and design efficiency. Numerous papers have also proposed methods of selecting appropriate conveyors for different manufacturing transportation purposes [13–16]. Autonomous guided vehicles (AGVs) were useful for manufacturing material transportation [17–19]. AGVs are often used to transport goods and materials using the optimal and shortest paths for enhanced efficiency in manufacturing operations. In addition, material handling equipment (MHE) has been utilised in manufacturing plants to optimise manufacturing processes and activities [20]. Thus, MHE, such as trolleys and push carts, can significantly reduce the physical efforts of manual workers while increasing production efficiency. Sonpimple, et al. [21] proposed a design of an innovative motorised hand truck, which can optionally ease the manual operations of roof tile workers and potentially reduce the prevalence of MSDs. Widyotriatmo, et al. [22] proposed implementing an innovative and autonomous forklift for material handling in the manufacturing process. In addition, unmanned autonomous forklifts can deliver simple tasks and avoid obstacles with minimal human intervention. These systems can reduce the frequency of workplace accidents.

Table 3 summarises key findings on inspection systems from past studies. Various defect identification models that utilised vision cameras to identify defects in objects were proposed by several researchers [23–33]. These studies mentioned the captured data and photos for machine-based learning and convolutional neural networks (CNN). The findings from the existing literature showed that it is essential to inspect the top and bottom half of the tiles during the roof tile inspection process. In this situation, it would be necessary to turn the tiles around to inspect the bottom half of the tiles. Hence, a mechanism or system must be incorporated into the conceptualisation process so the roof tile can be flipped for a full inspection on both sides.

Table 2. Summary of key findings of past studies on transportation systems.

System	Key Findings	Ref.
Conveyor System	- TTC conveyor system. - DFMA redesign resulted in improved cost and design efficiency.	[12]
	- Prediction of optimal operating conditions on a belt conveyor system. - Provided detailed calculation and analysis of belt conveyors that can be simulated.	[16]
	- Design considerations of a belt conveyor system.	[14]
	- Selection of the optimal conveyor system. - Criteria include belt speed and width, motor selection, belt specification, shaft diameter, pulley, and gearbox selection.	[13]
AGV System	- AGV as a means of transportation. - Used in both production and assembly areas.	[18]
	- A task allocation method for multi-load AGVs based on adjacency combination and shortest path principles. - Proposed a method to prevent collisions and deadlocks among AGVs based on timetables of reservations.	[17]
	- Review of robots orientated towards manufacturing operations. - Measures of localising and controlling robots while addressing their safe use in collaborative applications with humans.	[19]
MHE	- Discussed the selection of MHE for manufacturing plants. - Produced appropriate MHE leads to physical effort reduction and production efficiency increase.	[20]
Industrial Trucks	- Design of innovative motorised hand truck for material handling. - Motorised design allows ease of manual operations.	[21]
Forklift	- Use of electric and liquid propane gas (LPG) forklifts for material handling. - Minimising carbon footprint produced by forklifts.	[34]
	- Utilisation and application of autonomous material handling vehicles. - Includes localisation, vision systems, and obstacle avoidance strategy.	[22]
	- Development of an unmanned autonomous forklift. - Simulations of trajectory generation of the unmanned forklift between two arbitrary configurations.	[35]

Table 3. Summary of key findings of past studies on inspection systems.

Key Findings	Ref.
- Automated and computerised methods to automatically classify marble slabs. - Slabs moved on conveyor belts. - An electromechanical system was designed to sort out the classified marble slabs.	[23]
- Capturing data with a 3D colour camera. - Studying slate slab traits using computer vision algorithms. - Accurately detect traits and characterise the slabs.	[29]
- Using NIR cameras to capture apple images. - Using the YOLO V4 network for online apple defects detection. - Able to accurately detect defects on the surface of the apple.	[27]
- Machine learning-based image processing for online defect-recognition in additive manufacturing. - Achieved by automated image feature learning and feature fusion. - Effective detection of defects due to process non-conformities.	[25]
- Collected a large number of concrete crack images into a database. - A fast detection network architecture was proposed to detect apparent concrete cracks in slab tracks using dilated convolution based on deep learning. - Improved detection method of slab tracks.	[33]
- Surveyed the advances in vision-based defect recognitions. - Summarises the advantages, disadvantages, and application scenarios.	[28]
- Proposition of CrackForest, a novel road crack detection framework based on random structured forests. - Introduction of random structured forests to generate a high-performance crack detector, which can identify arbitrarily complex cracks.	[31]
- Details of automatic inspection of ceramic tiles using computer vision. - Detection of the pinhole, cracks, colour variation, and abnormalities in chromatic and structural properties of textured tiles.	[24]
- Deep learning-based methods were used to classify surface defects. - The defect dataset was created with 150 tile images from the crack, fleck, pore, scratch, and spot defects.	[26]
- Proposed a simple but effective convolutional neural network to learn the similarities between closely related raw pixel images. - Evaluated the classification performance of the proposed method using a collection of tile surface images of cracked and no-cracked surfaces.	[32]
- Developed a method to detect concrete surface defects using a deep neural network (DNN)-based on light detection and ranging (LiDAR) scanning. - Use of PointNet, a CNN extensively used for analysing 3D point sets. - Despite the small size of the training dataset, promising initial results were obtained.	[30]

The summary of key findings on flipping systems from past studies is demonstrated in Table 4. Several researchers proposed robotic arms for object reorientation and manipulation [36–41]. Generally, the designs produced robotic arms to pick, place, and reorient objects with mechanical arms.

Chavan-Dafle, et al. [42] proposed a two-phase gripper to reorient and grasp objects. Once reoriented to an upright position, the object was easily scanned on both sides. Meanwhile, Aggarwal, et al. [43] reported a smart flipping system integrated into conveyor belts. The smart flipping system could flip an object directly on the conveyor belt, and is perfectly suited for fast object reorientation.

Table 4. Summary of key findings of past studies on flipping systems.

System	Key Findings	Ref.
Robotic Arm	- Soft robots have greater potential for dexterous and smooth motions with inherent compliance. - DOIS (Dexterous Origami-inspired Soft) robot allows for flexible motion, such as object reorientation.	[37]
	- ReorientBot, a vision-based manipulation system. - Visual scene understanding with pose estimation and volumetric reconstruction using an onboard red green blue-depth (RGB-D) camera. - Learned waypoint selection for successful and efficient motion generation for reorientation.	[41]
	- Concept generation of a robotic arm. - Development of the hardware and software for an accelerometer-controlled robotic arm. - Able to pick and place objects extremely fast and easily.	[38]
	- Integration of laser profile sensor to an industrial robotic arm for automating the quality inspection in manufacturing processes, which requires manual and labour-intensive work. - Laser profile sensor mounted on a six-degrees-of-freedom robot for quality inspection.	[36]
	- Direct collocation-based trajectory optimisation methodologies were utilised to realise trajectories in a robotic arm platform applied to flipping burgers as an example of non-prehensile object manipulation.	[39]
	- The object manipulation method to regulate the position and altitude of an object in the task space with dynamic stability by using a triple soft-fingered robotic hand system.	[40]
Upright scanning	- Two-phase gripper to reorient and grasp objects. - Relevant industrial applications where parts were often presented on lying trays or conveyors.	[42]
Flipping Conveyor	- Development of a smart flipping system in the conveyor belt to reorient products upside down.	[43]

The summary of key findings on manufacturing systems from recent studies is revealed in Table 5. In the roof tile transportation system, Butt and Jedi [12] proposed a table top chain conveyor system with improved cost and design efficiency. Furthermore, Salawu, et al. [16] proposed the optimal belt conveyor operating conditions and designs. In another study, Soufi, et al. [20] discussed the selection of various MHEs for manufacturing plants. An innovative motorised hand truck was also proposed by Sonpimple, et al. [21] to ease manual operations.

In flipping mechanisms, a smart flipping mechanism that can be integrated into conventional belt conveyors was proposed by Aggarwal, et al. [43]. Consequently, the design could reorient products on the conveyor belt into an overturned position.

Designs that use vision-based cameras to identify surface defects on objects in inspection systems were proposed by several researchers [23,29,30,32,33]. The captured data and photos for machine-based learning and CNN were prevalent in these studies.

Table 5. Summary of key findings of recent studies on manufacturing systems.

Content	Strengths	Ref.
Transportation system	- TTC conveyor system. - DFMA redesign resulted in improved cost and design efficiency.	[12]
	- Prediction of optimal operating conditions of a belt conveyor system. - Provides detailed calculation and analysis of belt conveyors that can be simulated.	[16]
	- Discussed the selection of MHE for manufacturing plants. - Having appropriate MHE leads to a reduction in physical effort and increased production efficiency.	[20]
	- Design of innovative motorised hand truck for material handling. - Motorised design allows ease of manual operations.	[21]
Flipping system	- Development of a smart flipping system in the conveyor belt to reorient products upside down.	[43]
Inspection system	- Automated and computerised methods to automatically classify marble slabs. - Slabs moved on conveyor belts. - An electromechanical system was designed to accomplish the task of sorting out the classified marble slabs.	[23]
	- Capturing data with a 3D colour camera. - Studying slate slab traits using computer vision algorithms. - Accurately detect traits and characterise the slabs.	[29]
	- Collected a large number of concrete crack images into a database. - Fast detection network architecture using dilated convolution based on deep learning was proposed to detect apparent concrete cracks in slab tracks. - Improved detection method of slab tracks.	[33]
	- Proposed a simple but effective convolutional neural network to learn the similarities between closely related raw pixel images. - Evaluated the classification performance of the proposed method reported in ref [32] using a collection of tile surface images of cracked and no-cracked surfaces.	[32]
	- Developed a method to detect concrete surface defects using a DNN-based on LiDAR scanning. - PointNet, a CNN used extensively for analysing 3D point sets. - Despite the small size of the training dataset, promising initial results were obtained.	[30]

Table 6 summarises the key findings of usability evaluation methods from recent studies. Barosz, et al. [44] proposed using overall equipment effectiveness (OEE) to perform an efficiency analysis of implementing industrial robots in manufacturing lines. Alternatively, several researchers proposed implementing the American Productivity Centre (APC) model to measure productivity [45–47]. The model could determine efficiency performances in the creative and production industries and other industries. Using simulations, Kliment, et al. [48] also proposed an efficiency evaluation model. Mishra, et al. [49] proposed the application of t-tests, which can determine the presence of a significant difference between the means of two groups and their relations.

Table 6. Summary of key findings of recent studies on usability evaluation methods.

Advantages	Ref.
- Efficiency analysis of implementing industrial robots in manufacturing lines. - Implementation of OEE. - Detailed calculations of OEE using availability, performance, and quality formulas.	[44]
- Efficiency performance and productivity of creative industries. - Measured productivity levels using Marvin E Mundel and the APC models.	[47]
- Implemented the APC productivity measurement model.	[45]
- Implemented the APC productivity measurement model to measure the productivity of the palm oil milling industry.	[46]
- Production efficiency evaluation and quality improvement of products using simulation software.	[48]
- Application of t-test. - Analysis of variance and covariance.	[49]

According to the studies above, there is a lack of research that identifies the most appropriate concept to be used in the transportation and inspection systems for the manufacturing of roof tiles. Furthermore, more studies focusing on protocol-testing for roof tile manufacturing transportation systems are needed with regard to usability. In addition, TRIZ has neither been used to support the general concept selection process, nor the general protocol selection process of roof tile transportation and inspection systems.

Therefore, this study aimed to investigate the development of a transportation concept for roof tile manufacturing and its usability testing protocol with the support of the TRIZ approach. The study aimed to improve efficiency [44], reliability [50], and productivity [47] compared to manual processes. Additionally, the methodology includes the conceptualisation and selection of an appropriate roof tile manufacturing system for the transportation and inspection of the roof tiles. Once the system was selected, a usability evaluation plan was developed to test the selected concept. The following research objectives were proposed in this study:

1. To propose the most appropriate transportation and inspection system for the roof tile manufacturing industry in Indonesia with the support of the TRIZ approach;
2. To propose an efficient, reliable, and productive protocol in evaluating the efficacy of the proposed manufacturing system compared to the manual process with the support of the TRIZ approach.

2. Methodology

2.1. Conceptualisation of Roof Tile Manufacturing System

In this study, the system was compartmentalised into three categories (transportation, flipping, and inspection systems) to conceptualise an appropriate roof tile manufacturing system (see Figure 1). The flipping and inspection systems were performed through the transportation system, which moves the roof tiles across a factory. Subsequently, the flipping system flipped the roof tiles to ensure that the proper inspection was performed on both sides of the roof tiles. Lastly, the inspection system detected the defects on the manufactured roof. In addition, a transportation system was chosen with concept screening and scoring, and the most appropriate method to transport the roof tiles was determined. The criteria used for the screening and scoring processes included cost, durability, reliability, versatility, risk to the product, and efficiency.

In the effective inspection of both sides of the roof tiles, a flipping mechanism was included in the manufacturing process to flip the tiles before they passed the inspection system. The smart flipping system proposed by Aggarwal, et al. [43] was chosen due to its suitability for the present study, which incorporated the flipping mechanism with belt conveyors. Moreover, the smart flipping system was deemed to be appropriate for roof tile production as it requires minimal worker interference and poses a negligible risk to the roof tiles. Thus, this mechanism was selected from all the concepts by default.

Based on the advantages and disadvantages of the three proposed inspection systems in the literature, the inspection system proposed by Alper Selver, et al. [23] was chosen. The inspection system was not chosen through a conventional systematic selection process as the inspection systems identified via the literature were all similar. Furthermore, it is difficult to differentiate among the systems via standard means, such as concept screening and scoring. After observing the advantages and disadvantages of the inspection systems (see Table 7), the inspection system proposed by Alper Selver, et al. [23] was deemed to be the most suitable for this study. The proposed inspection system can automatically classify marble slabs, similar to roof tiles.

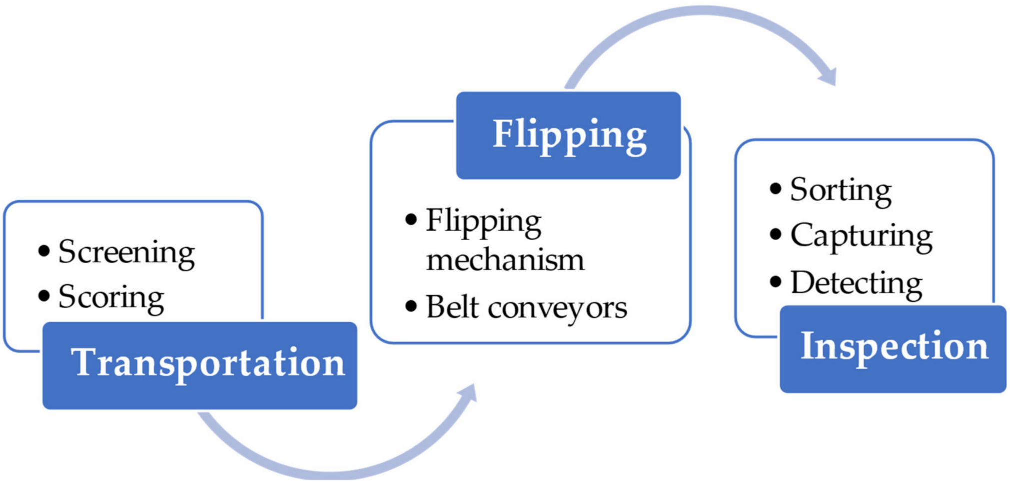

Figure 1. The proposed process of the roof tile manufacturing system.

Table 7. Advantages and disadvantages of several inspection systems.

Advantages	Disadvantages	Ref.
- Automated and computerised methods to automatically classify marble slabs. - System can be embedded into conveyor lines. - Able to sort out the classified marble slabs.	- In challenging samples, a longer period may be needed to identify all the defects.	[23]
- Capturing data with a 3D colour camera. - Able to study slate slab traits using computer vision algorithms. - Accurately detect traits and characterise the slabs.	- False squaring and flower-like staining detection may be unrelated to roof tiles.	[29]
- Able to detect concrete surface defects using a DNN-based on LiDAR scanning. - Performed well for deeper defects.	- Performed averagely for slight defects. - Only tested with a small sample size. - All kinds of defects are only categorised into one class.	[30]

The study proposes four transportation concepts (see Figure 2) based on the three process categories of the roof tiles manufacturing systems. Subsequently, a concept was selected based on several criteria, as described in Section 2.2. Concept 1 utilises a TTC conveyor system for the transportation system of the roof tiles. Since TTC conveyors use metal plates and chains in their design, they are ideal for high-strength and high-speed applications. Similar to all the other concepts, the flipping and inspection mechanisms in Concept 1 were proposed by Aggarwal, et al. [43] and Alper Selver, et al. [23], respectively.

Concept 2 incorporates using a belt conveyor system as the transportation method of the roof tiles. The inexpensive cost and easy-to-use design allow it to be one of the most versatile conveyor systems in the market [51]. Therefore, the flipping and inspection mechanisms for this concept were adopted from the works of Aggarwal, et al. [43] and Alper Selver, et al. [23], respectively.

Concept 3 follows the AGV system, which the transportation system in this concept utilises AGVs to transport the roof tiles from one place to another in the factory. An AGV is suited for material handling as it does not require much user intervention. Additionally, it is typically used repetitively moving large volumes of material [52]. Hence, the flipping and inspection mechanisms for this concept were also adopted from the works of Aggarwal, et al. [43] and Alper Selver, et al. [23], respectively.

Concept 4 uses motorised hand trucks to transport the roof tiles proposed by Sonpimple, et al. [21]. A motorised hand truck puts significantly less strain on the workers and reduces the chances of sustaining MSDs. Thus, the flipping and inspection mechanisms for this concept were also adopted in the works of Aggarwal, et al. [43] and Alper Selver, et al. [23], respectively.

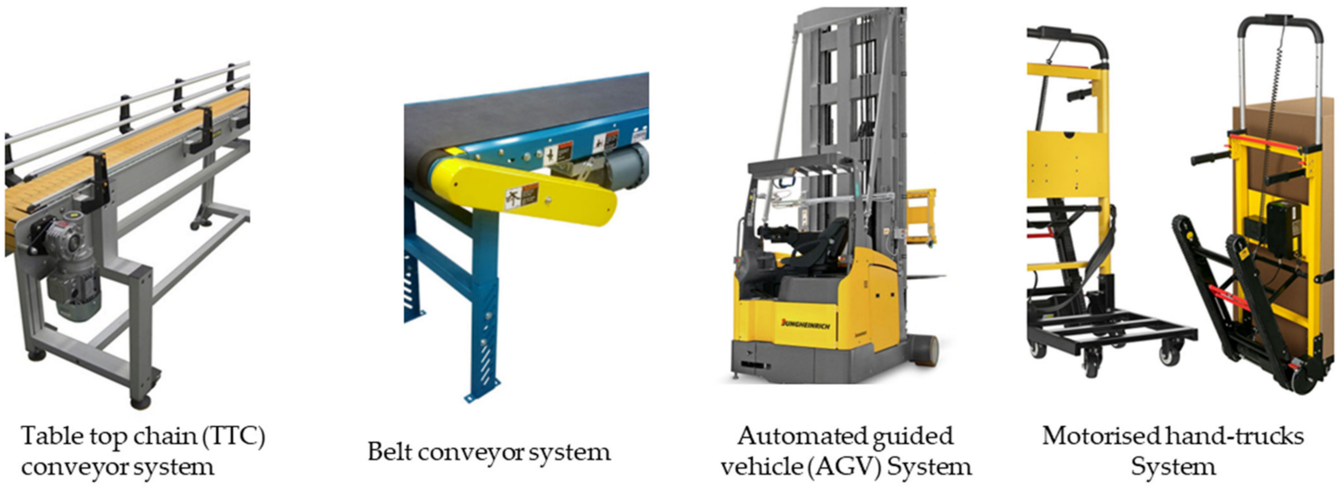

Figure 2. Proposed concepts for the roof tile transportation system.

2.2. Concept Selection

The transportation concept designs were screened based on several selection criteria based on the fundamental concept of sustainability. These criteria are also vital in achieving productivity and efficiency of implementing the improvement on the transportation of roof tile manufacturing. These selection criteria included cost, durability, reliability, versatility, risk to the product, efficiency, and safety. Each criterion was described as follows:

Cost: Cost is an important factor in ensuring a profitable outcome. The cost of the manufacturing system should be within an acceptable range. Likewise, the cost of a product is a crucial criterion, as a high manufacturing cost may result in an overpriced product. Furthermore, a costly production may negatively impact returns, which contradicts the purpose of the roof tile production [53];

Durability: Durability is the ability of a product to last a long time without significant deterioration. Hence, a durable manufacturing system helps the environment by conserving resources, reducing waste, and reducing the environmental impacts of repair and replacement [54,55];

Reliability: Increased manufacturing reliability will increase product output and reduce the processing time of incoming raw materials to become the final product. Improved reliability also allows for a faster and safer manufacturing flow [50]. Thus, this will result in reduced losses in delayed deliveries, overproduction, work in progress, and energy expenditure;

Versatility: When a product can be used across multiple sections of the production line, it adds value and decreases costs [56]. Therefore, acquiring versatility in tools produces a more efficient manufacturing process and allows for greater completion of various tasks;

Risk to the product: Defective products directly incur costs to the production factories or companies, which low quality can translate to a high cost [57]. When the level of defective products shipped to customers becomes too high, a significant negative impact on brand image and reputation can reduce future sales. In addition, critical manufacturing defects put a business at risk of being liable for damages. Such defects that slip through the quality control process will likely cause harm to the product users;

Efficiency: Manufacturing efficiency is the ability to do or produce something without wasting materials, time, or energy. A high-efficiency percentage is ideal to ensure that goods are produced at the lowest average cost [58]. An enhanced selection of raw materials can also lead to increased efficiency through improved ease of handling and consistency of supplies;

Safety: Manufacturing safety is an important criterion for this study as it keeps people alive and unharmed. A safe workplace for employees must be created to prevent industrial accidents, injuries, illnesses, and deaths [59].

Several transportation methods are commonly used in manufacturing lines to transport goods around the factory. The appropriate choices of transportation methods include TTC and belt conveyors, AGVs, and motorised hand trucks. A concept was proposed for each transportation method to better visualise its efficacy in the roof tile manufacturing process. A concept selection was then performed to select the most suitable transportation method for the roof tile manufacturing system. Ratings were given to the systems according to the criteria mentioned above. The first stage narrowed down the concepts, including concept screening, where all the concepts were compared against a selected reference transportation method. Upon comparison, two of the most suitable concepts were selected for the second stage of concept selection, the concept scoring stage. Ratings were given to the transportation methods according to the established selection criteria. The ratings are defined from 1 to 5, as tabulated in Table 8.

Table 8. Rating scales to fulfil the criteria of transportation.

1	2	3	4	5
Very poor	Poor	Average	Good	Excellent

Each criterion was given a weightage (W), which the score (S) was multiplied by the weight (WS = W $\times$ S) to measure the weighted score (WS). The concept with the highest weighted score was then selected as the most suitable transportation method for roof tile manufacturing. The main author of this study conducted the screening and scoring with some assistance from the co-authors. However, the main author exclusively recommended the scores for each protocol based on his particular expertise and familiarity with the various roof tile manufacturing processes. The main author also took the lead in designing this study and had a solid understanding of the costs and resources to be considered. The co-authors of this study agreed with the assessments of the main author, as he has an excellent understanding of roof tile manufacturing processes. Similar processes have been used in other studies [60–62].

2.3. Conceptualisation of Protocol

After reviewing the key findings of recent studies, four types of protocols were developed to test the efficiency, reliability, and productivity of the manufacturing systems.

Protocol 1: Barosz, et al. [44] proposed an efficiency analysis of the manufacturing line with industrial robots and human operators. A method known as the OEE metric was used to evaluate the efficiency and reliability in the performance of the workstation for short and long terms. The OEE calculates the availability, performance, quality, and efficiency of a manufacturing system.

Protocol 2: Several researchers proposed implementing the APC method to determine the productivity of industries [45–47]. The APC method covers the shortcomings of other productivity measurement methods, such as OMAX, which only assesses the level of productivity weighting. Additionally, the APC method accounts for productivity, profitability, and price improvement indexes. The APC models are also useful in determining the productivity and efficiency of a proposed roof tile manufacturing system.

Protocol 3: Kliment, et al. [48] researched implementing a production efficiency evaluation model using simulations. The programmed simulations possibly observed the entire production process with the smallest details while capable of being stopped and restarted at any time. Thus, careful monitoring of the simulations can reveal bottlenecks, errors, and various shortcomings, which arise in a real production process. Simulations could also be successfully implemented into the proposed roof tile manufacturing system to determine the efficiency of the manufacturing systems and optimise the process.

Protocol 4: Mishra, et al. [49] researched the use of t-tests, which are used to test whether the mean difference between two groups is statistically significant. The method comprises null and alternative hypotheses. The null hypothesis states that both means are statistically equal. In contrast, the alternative hypothesis states that both means are not statistically equal or different.

The same screening and scoring methods from the conceptual development phase were adopted for the protocol development stage.

2.4. Supporting Concept and Protocol Selection with TRIZ

The theory of inventive problem solving (TRIZ) is used to support the concept and protocol selection process. TRIZ is an international creativity system developed between 1946 and 1985 by engineer and scientist Genrich S. Altshuller and his colleagues in the USSR. It is successfully used in various fields, including architecture, automotive, banking, construction, and the development of energy-saving products [63–67]. Due to its versatility and successful application in different fields, this study chose TRIZ to support the concept and protocol selection for roof tile transportation and inspection systems.

The TRIZ process has been cited in several papers [68–71], and includes the following flow:

- Formulation of engineering contradiction;
- Identification of system parameters in engineering contradiction;
- Intersection of system parameters within TRIZ contradiction matrix;
- Selection of inventive principle from the intersection of system parameters;
- Proposal of concept or solution based on selected inventive principle.

The results of the TRIZ approach in this study are intended to support the results of the screening and scoring process for the concepts and protocols. The goal of this approach is to facilitate the decision-making process when selecting the concept and protocol.

3. Results and Discussion

3.1. Concept Selection for an Appropriate Transportation System

3.1.1. Concept Screening Results

Table 9 shows the concept screening results, solely based on the existing literature, that weighed the strengths and weaknesses of each concept. The four concepts were screened using the established selection criteria. The criteria included cost, durability, reliability, versatility, risk to the product, efficiency, and safety. Concept 1 was chosen as the reference due to its durability, reliability, and efficient performance. Concepts 2, 3, and 4 were compared to the reference. The symbol "+" was given to concepts that performed better than the reference in a specific criterion. The symbol "−" was given to the concepts that performed more poorly than the reference in a specific criterion. Finally, a score of zero or "0" was given if the performance of the concept matched the reference in a specific criterion. The net score was calculated, and the two best concepts (Concepts 1 and 2) were chosen for the second stage, which included the concept scoring process.

Table 9. Summary of the concept screening results from Concepts 1 to 4.

Criteria	Concepts			
	1 (TTC) (Reference)	**2 (Belt)**	**3 (AGV)**	**4 (Hand Truck)**
Cost	0	+	+	+
Durability	0	−	−	−
Reliability	0	−	−	−
Versatility	0	+	−	−
Risk to the Product	0	+	+	+
Efficiency	0	+	-	−
Safety	0	+	+	0
Sum of "+"	0	5	3	2
Sum of "0"	10	0	0	1
Sum of "−"	0	2	4	4
Net score	0	3	−1	−2
Ranking	2	1	3	4
Decision	**Continue**	**Continue**	**Eliminated**	**Eliminated**

3.1.2. TRIZ Supporting Results for Concept Selection

Based on the theory of inventive problem solving (TRIZ), Concepts 1 to 4 were analysed with regard to an engineering contradiction. Hand trucks (Concept 4) are usually semi-automated. Although fully automated versions of AGV systems also exist, it has been observed that Concept 3 (AGV) has the potential to also become semi-automated if cost were a major criterion in concept selection. Therefore, the following engineering contradiction (EC1) was formulated:

> *EC1: If a semi-automated concept is applied, then the productivity is better than using manual labour (Parameter 39: Productivity), but the rate of work performed is not optimal compared to a fully automated concept (Parameter 21: Power).*

The system parameter identified for the positive statement (the "then" statement) was parameter 39 (Productivity), and the parameter identified for the negative statement (the "but" statement) was parameter 21 (Power). After intersecting the two parameters in the TRIZ contradiction matrix, it was found that the most appropriate inventive principle to solve EC1 was Principle 20 (Continuity of Useful Action). This principle dictates that work should be carried out continuously, with all parts of the object working under a full load all the time, eliminating any idle or intermittent action or work.

Due to the possibility that Concepts 3 (AGV) and 4 (Hand truck) could become semi-automated options if cost were to be a critical criterion, it made sense to narrow the selection down to the conveyor system concepts, namely Concepts 1 (TTC) and 2 (Belt). The TRIZ results thus supported the results of the general concept screening.

3.1.3. Concept Scoring Results

Table 10 demonstrates the concept scoring results used to determine the finalised concept. Each criterion carries a different weight based on its importance to the project. In this project, high productivity and a low defect rate are important outcomes for roof tile manufacturers [71,72], so the criteria of risk to the product and efficiency are weighted as the highest criteria compared to the others. Durability and versatility are also weighted somewhat higher than the other criteria, as these factors have a significant impact on waste reduction, product longevity and cost [54–56]. The concepts were rated from 1 to 5 (as shown in Table 8: 1–Very poor fulfilment of criteria; 5–Excellent fulfilment of criteria). The concept with the highest weighted score was selected as the finalised concept. Compared to Concept 1, Concept 2 was observed to be superior in most criteria. Thus, Concept 2 was chosen as the final concept.

Table 10. Summary of the concept scoring results in Concepts 1 and 2.

Criteria	Weightage (%)	Concepts	
		1 (TTC)	2 (Belt)
Cost	10	2	4
Durability	15	4	3
Reliability	10	4	4
Versatility	15	4	5
Risk to the Product	20	3	5
Efficiency	20	4	4
Safety	10	3	4
Weighted score		3.5	4.2
Ranking		2	1
Decision		**Eliminated**	**Chosen**

Based on the results, Concept 2 scored the best in performance compared to the other concepts with regard to cost, durability, reliability, versatility, risk to the product, efficiency, and safety. In terms of cost, Concept 2 performed considerably better than Concept 1. Belt conveyors are known to be one of the cheapest types of conveyors in the market compared to the sturdier TTC conveyors, which are normally more expensive [73]. Moreover, the belt conveyor is cheaper when compared to AGVs and motorised hand trucks due to its simplicity and ease of maintenance [74].

The minimal worker interference of the belt conveyors also reduces the number of workers needed. Thus, this concept can significantly reduce labour costs. Regarding durability, TTC conveyors were slightly ahead of belt conveyors due to their metal build, making them ideal for high-strength and high-speed applications.

Regarding reliability, Concept 2 excelled compared to the other concepts. Conveyor systems are generally very reliable, with simple designs requiring motors. Nevertheless, AGV systems require intricate layout planning (which could result in unwanted errors). Concept 2 also performed better in versatility compared to the other concepts. The belt conveyor can be loaded from any place along the belt and then transported efficiently [73]. Comparatively, versatility can be restricted in other concepts as they must be loaded specifically on the transportation system and then transported efficiently.

Generally, Concept 2 posed minimal risk to the product, as belt conveyors are gentle on brittle products such as roof tiles. Comparatively, the hard surface of the TTC conveyor comes with the risk of the product toppling from the AGVs or hand trucks and breaking. This demonstrated that the belt conveyor would be more suitable for roof tile manufacturing. Concept 2 was the most efficient system out of all the other concepts, as conveyors help save time by allowing materials to move quickly between the opposite ends of the plant [51]. The concept also eliminates the need to manually unload materials, which is usually needed for the AGV and hand-truck systems. Moreover, the speed controls can be adjusted to achieve the optimal production speed to reduce time wastage and increase roof tile production.

In terms of safety, belt conveyor systems work efficiently. Installing a suitable conveyor in the manufacturing system means having fewer workers, which in turn reduces the number of workplace accidents. There would also be fewer demands (if any) for carrying heavy loads and repeating specific movements, which results in significantly reduced chances of injuries or MSDs [51].

Based on the data, Concept 2 was the most appropriate transportation system for roof tile manufacturing due to its superior performance in selection criteria, including cost, durability, reliability, versatility, risk to the product, high efficiency, and safety.

3.2. Selection for Appropriate Protocol

3.2.1. Protocol Screening Results

Table 11 depicts the protocol screening results that weighed the strengths and weaknesses of each protocol. The four protocols were screened using the established selection criteria. The criteria included simplicity, cost, time, suitability, and ease of implementation. Protocol 2 (APC Model) was chosen as the reference due to its ability to determine the efficiency of manufacturing systems for various industries [45–47]. Alternatively, Protocols 1, 3, and 4 were compared to the reference. The symbol "+" was given to protocols that performed better than the reference in a specific criterion. The symbol "−" was given to the protocols that performed more poorly than the reference in a specific criterion. Finally, a score of zero or "0" was recorded if the performance of the protocol matched the reference in a specific criterion. The net score was calculated, and the two best protocols (Protocols 2 and 4) were chosen for the second stage, which included the protocol scoring process.

Table 11. Summary of the protocol screening results from Protocols 1 to 4.

Criteria	Protocols			
	1 (OEE)	**2 (APC) (Reference)**	**3 (Simulation)**	**4 (T-Test)**
Simplicity	0	0	−	+
Cost	−	0	−	0
Time	0	0	+	+
Suitability	0	0	−	+
Ease of Implementation	−	0	−	+
Sum "+"	0	0	1	4
Sum "0"	3	5	0	1
Sum "−"	2	0	4	0
Net score	−2	0	−3	4
Ranking	3	2	4	1
Decision	**Eliminated**	**Continue**	**Eliminated**	**Continue**

3.2.2. TRIZ Supporting Results for Protocol Selection

Observing Protocols 2 (APC) and 4 (T-test), it was found that the APC method was largely based on longitudinal data on the Productivity Index, Profitability Index and Price Improvement Index [46]. The APC method covered the measurement of the productivity indicator well. However, if the simplicity and time in completing the assessment were key criteria for protocol selection, obtaining longitudinal data may not be the best practice when testing a proof of concept. Such an option could prove time-consuming and inefficient for the researcher, as several layers of bureaucracy may have to be gone through before the data are successfully backed up. Given the prevalence of human error in manufacturing organisations [75–78], the time-consuming process can result in the loss of critical information needed to evaluate the concepts, which would require the researcher to repeat the entire evaluation. Based on the above concerns, an engineering contradiction (EC2) was formulated:

EC2: If longitudinal data on productivity was used in the assessment of the system, then a thorough productivity assessment can be performed (Parameter 39: Productivity), but there is a risk of losing more important Information due to human error in the time-consuming process of evaluation (parameter 24: loss of information).

The negative statement in EC2 was linked to Productivity (System parameter 39) and the positive statement to Loss of Information (System parameter 24). When the two parameters in the TRIZ contradiction matrix were intersected, the most appropriate inventive principle selected was Feedback (Inventive principle 23). Applying this principle involves introducing feedback mechanisms to improve a process or action. If feedback already exists, its size or impact should be changed. In this context, the t-test method seems more appropriate than the APC method, as it involves shorter feedback mechanisms in the form of a control and treatment setting with only a limited number of samples. Such a method is more suitable for testing a proof of concept than the APC method, which uses more detailed and longer-term data for a more accurate representation.

3.2.3. Protocol Scoring Results

The protocol scoring results to determine the finalised protocol are tabulated in Table 12. Each criterion carries a different weight based on its importance to the project. The protocols were rated from 1 to 5 (as shown in Table 8: 1–Very poor fulfilment of criteria; 5–Excellent fulfilment of criteria). The protocol with the highest weighted score was selected as the finalised protocol. Hence, Protocol 4 was superior in most criteria compared to Protocol 2. Protocol 4 was chosen for the usability evaluation of the roof tile manufacturing system. This decision is consistent with the decision supported by TRIZ.

Table 12. Summary of the protocol scoring results of Protocols 1 and 2.

Criteria	Weightage (%)	Protocols	
		2 (APC)	4 (T-Test)
Simplicity	20	3	4
Cost	15	5	5
Time	10	3	5
Suitability	30	4	5
Ease of Implementation	25	3	4
Weighted score		3.6	4.55
Ranking		2	1
Decision		**Eliminated**	**Chosen**

Protocol 4 was chosen as the most appropriate protocol for this project. The protocol scored the best overall performance compared to the other concepts in terms of simplicity, cost, time, suitability, and ease of implementation. Furthermore, the protocol excelled in its simplicity compared to the other protocols, and can be designed to fit each situation, while the complexity depends on the user's decision.

Regarding cost, both Protocols 2 and 4 scored excellently as the tests only require data, which can be easily collected without requiring any heavy expenses.

The t-test method requires significantly less time to execute than Protocol 2 because the data are easily obtained through usability tests. Conversely, the APC model data requires detailed data collection (years) for an accurate representation [46].

In this study, the t-test method was the most suitable among the other protocols. The versatility of the t-tests allows its implementation in any situation. It is the only protocol to administer efficiency, reliability, and productivity tests. On the contrary, other models, such as the APC method, only focused on productivity and profitability [46].

The t-test method was considered superior in terms of ease of implementation compared to the APC method. In addition, a t-test can be implemented without requiring years of collected data, is more versatile than the APC method, and can produce the desired results. Thus, the t-test method was the most suitable protocol for this study.

3.3. Finalised Protocol

3.3.1. Efficiency Test

The efficiency test was performed to test the efficiency of the roof tile transportation and inspection systems in comparison to the manual process with the following efficiency test questions as follows:

a. How fast can the roof tiles be transported with the system (test group) compared to the manual process (control group)?
b. How fast can the system (test group) be completed with the roof tile inspection compared to the manual (control group) inspection process?

Measurables and Hypotheses:

a. Time taken for the roof tiles to be transported from point A to B.
    i. Null hypothesis, H0a: The time taken to transport the roof tiles from point A to B with the system (test group) does not significantly differ from the manual process (control group) ($p > 0.05$).
    ii. Alternative hypothesis, H1a: The time taken to transport the roof tiles from point A to B with the system (test group) significantly differs from the manual process (control group) ($p < 0.05$).
b. Time taken for roof tiles to be inspected.
    i. Null hypothesis, H0b: The time taken to complete the roof tile inspection with the system (test group) does not significantly differ from the manual inspection process (control group) ($p > 0.05$).
    ii. Alternative hypothesis, H1b: The time taken to complete the roof tile inspection with the system (test group) significantly differs from the manual inspection process (control group) ($p < 0.05$).

3.3.2. Reliability Test

The reliability test questions were set to test the reliability of the roof tile transportation and inspection systems in comparison to the manual process as follows:

a. How foolproof can transporting roof tiles be with the system (test group) compared to the manual process (control group)?
b. How foolproof can inspecting roof tiles be with the system (test group) compared to the manual inspection process (control group)?

Measurables and Hypotheses:

a. Several errors occur when roof tiles are transported from point A to B.
    i. Null hypothesis, H0a: The number of errors when transporting the roof tiles from point A to B with the system (test group) does not significantly differ from the manual process (control group) ($p > 0.05$).
    ii. Alternative hypothesis, H1a: The number of errors when transporting the roof tiles from point A to B with the system (test group) significantly differs from the manual process (control group) ($p < 0.05$).
b. Several errors occur when roof tiles are inspected (e.g., defect not being detected, or defect detected when there was none).

i. Null hypothesis, H0b: The number of errors when inspecting the roof tiles with the system (test group) does not significantly differ from the manual inspection process (control group) ($p > 0.05$).
ii. Alternative hypothesis, H1b: The number of errors when inspecting the roof tiles with the system (test group) does not significantly differ from the manual inspection process (control group) ($p < 0.05$).

3.3.3. Productivity Test

The following productivity test questions were established to test the productivity of the roof tile transportation and inspection systems in comparison to the manual process as follows:

a. How productive can roof tiles transportation be with the system (test group) compared to the manual process (control group)?
b. How productive can roof tiles inspection be with the system (test group) compared to the manual inspection process (control group)?

Measurables and Hypotheses:

c. A total number of roof tiles transported from point A to B at a fixed timeframe.
   i. H0a: The number of roof tiles transported from point A to B with the system (test group) does not significantly differ from the manual process (control group) ($p > 0.05$).
   ii. H1a: The number of roof tiles transported from point A to B with the system (test group) significantly differs from the manual process (control group) ($p < 0.05$).
d. A total number of roof tiles inspected at a fixed timeframe.
   i. H0b: The number of roof tiles inspected with the system (test group) does not significantly differ from the manual inspection process (control group) ($p > 0.05$).
   ii. H1b: The number of roof tiles inspected with the system (test group) significantly differs from the manual inspection process (control group) ($p < 0.05$).

3.3.4. Proposed Analyses

The mean analysis can compare if the parameters of the test group are higher or lower than the control group in terms of efficiency, reliability, and productivity. Additionally, Cohen's d can evaluate the effect size. Power analysis can also measure the statistical power of sample size. Meanwhile, the normality test can assess if the data is normally distributed. The two-sample variance test can calculate if the variances are equal or unequal. Furthermore, the two-sample t-test can compare the test and control group data if the normality assumption adheres.

If the assumption of normality is violated, a Mann–Whitney U test can be used. The test can be used to compare the data between the test and control groups. Suppose the Mann–Whitney test is chosen in the end. In that case, the median analysis will be considered instead of the mean analysis.

3.3.5. Proposed Procedures

For each test, a total number of 10 batches of roof tiles can be used. Each batch comprises five roof tiles. Suppose the statistical power from the power analysis is less than 80%. In that case, more samples will be added for the tests until the statistical power surpasses 80%. The test group uses the roof tile transportation and inspection systems. In contrast, the control group uses the manual process that involves a participant (preferably from the roof tile industry). The participant will manually transport a batch of roof tiles and conduct the necessary inspections.

Efficiency-test group procedures:

1. The timer on the stopwatch is initiated when a roof tile is placed on the conveyor system at point A;
2. The timer is stopped when the conveyor successfully transports the roof tile to point B. Time is then recorded;
3. The timer is initiated when the automated roof tile inspection commences;
4. The timer is stopped when the roof tile inspection is completed and recorded;
5. Steps 1 to 4 are repeated until the total planned samples for the experiment have been achieved;
6. It is important to note that the time taken for Steps 1 to 2 and 3 to 4 should be separated;
7. It is important to note that the time taken is only valid if there are no errors during the trial.

Efficiency-control group procedures:

1. The timer on the stopwatch is initiated when the participant lifts and transports a batch of roof tiles at point A;
2. The timer is stopped when the batch of roof tiles is successfully transported to point B. Batch time is then recorded;
3. Steps 1 to 2 are repeated until the total planned samples for the experiment have been achieved;
4. It is important to note that the time taken for one transportation batch needs to be divided with the total samples within the batch (5 samples) to be fairly compared with the test group;
5. The timer is initiated when the participant's manual inspection of the roof tile commences;
6. The timer is stopped when the manual inspection for the roof tile is completed and recorded;
7. Steps 5 to 6 are repeated until the total planned samples for the experiment have been achieved;
8. It is important to note that the time taken for Steps 1 to 2 and 5 to 6 should be separated;
9. It is also important to note that the time taken is only valid if there are no errors during the trial.

Reliability-test group procedures:

1. Several errors occur when one roof tile is transported with the system from point A to B are recorded;
2. Several errors occur during the automated inspection are recorded;
3. Steps 1 to 2 are repeated until the total planned samples for the experiment have been achieved.

Reliability-control group procedures:

1. Several errors occur when one roof tile is transported manually from point A to B are recorded;
2. Several errors that occur during the manual inspection process are recorded;
3. Steps 1 to 2 are repeated until the total planned samples for the experiment have been achieved.

Productivity-test group procedures:

1. A fixed timeframe is established and clocked using a stopwatch;
2. The total number of roof tiles transported within this fixed timeframe by the system from point A to B is recorded;
3. Step 2 is repeated for five sessions;
4. The total number of roof tiles inspected within the fixed timeframe by the system is also recorded;
5. Step 4 is repeated for five sessions.

Productivity-control group procedures:

1. A fixed timeframe is established and clocked using a stopwatch;
2. The total number of roof tiles transported within this fixed timeframe manually from point A to B is recorded;
3. Step 2 is repeated for five sessions;
4. The total number of roof tiles inspected within this timeframe manually is also recorded;
5. Step 4 is repeated for five sessions.

4. Conclusions

The problem statement of this study asserted that there is a lack of studies that identify the most appropriate concept in the transportation and inspection systems of roof tile manufacturing systems. Furthermore, a lack of studies focusing on protocol testing regarding usability was observed. Finally, there were also no studies using the TRIZ approach to propose concepts and protocols for roof tile transportation and inspection systems. The main aim was to study the development of a roof tile manufacturing concept and its usability testing protocol for improved efficiency, reliability, and productivity with the support of the TRIZ approach. The main aim was achieved by researching the literature, which was comprised of various resources on transportation, flipping and inspection systems, suitable efficiency, reliability, and productivity measurement methods. The main aim was also achieved through the support of TRIZ approach which entailed the use of the engineering contradiction, system parameters, contradiction matrix, and inventive principles.

In conclusion, this study found that belt conveyors are the most effective transportation system for roof tile manufacturing. The TRIZ principle that supported the selection of the belt conveyor was Principle 20 (Continuity of Useful Action). The belt conveyor excels in cost, durability, reliability, versatility, low risk to the product, efficiency, and safety, making it the most appropriate choice for roof tile transportation. The flipping mechanism chosen included a smart flipping mechanism adopted from Aggarwal, et al. [43], which safely and effectively flips and reorients objects. This flipping system has also been incorporated into conveyor belts, facilitating its adoption for roof tile transportation and inspection systems. The inspection system was adopted from the work of Alper Selver, et al. [23], which included an inspection system that performs classification with clustering methods to identify the cracks and defects of marble slabs. Thus, these defects are very similar to those found in roof tiles. The inspection system was also incorporated with conveyor belts, allowing seamless integration into the roof tile transportation and inspection systems. The t-test method was the most appropriate protocol for this paper as it excels in simplicity, low cost, low time usage, suitability, and ease of implementation. The TRIZ principle that supported the selection of the t-test method was Principle 23 (Feedback).

The screening and scoring approach used in this study has been similarly applied to furniture design, food production and construction-related studies [79–81]. However, this is the first time that such an approach has been introduced in the evaluation of protocols for roof tile manufacturing systems. The similar t-test method chosen has indeed been used in studies testing biomechanical and landscaping equipment [60,82]. Therefore, there is a very high probability that the method of this study can be generalised beyond the production of roof tiles, and perhaps to other areas of building production, such as the production of concrete, wood, steel, plastic, glass, and bricks. This paper successfully proposed a suitable manufacturing system for the roof tile industry to boost productivity while reducing physical strain on workers. The paper also proposed a way to test the manufacturing system for its efficiency, reliability, and productivity.

4.1. Limitations

Due to the limitations in the resources of the project, no prototype was fabricated to test the concept and protocol proposed. The prototype would be too large and costly to fabricate for the researchers at this stage. The study also lacks usability feedback from the voice of the customer in the form of surveys, interviews, or focus groups. Lastly, the usability tests in this study only covered efficiency, reliability, and productivity, as this study was production-centric by nature and prioritised such aspects. Other usability metrics, such as success rate and satisfaction, were not accounted for.

4.2. Directions for Future Research

Firstly, the proposed system may be built to analyse its applicability to the manufacturing sector further. The suggestions may provide researchers with real-world insights into the actual effectiveness of the system in the roof tile manufacturing industry. Future researchers may also explore adding a sortation system after the inspection, which can remove any defective roof tiles. Therefore, this solution could further increase the productivity and speed of production and further reduce the manual labour required during the production process. Moreover, the developed concepts need to be further investigated in order to provide an overview of the acceptance of the developed systems in the factory as well as the mentality of management, and financial resources for mechanisation and automation.

Lastly, the CO_2 emissions from the developed transportation system in roof tile manufacturing companies should be taken into consideration because transportation contributes to the global warming and CO_2 emissions as reported in the Refs. [83–85].

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