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A Sub-Saharan African Airport Mechanical Equipment Failure Assessment Using Joint FMECA-GRA Method Based on Technical Process Efficiency

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Abstract

This article establishes how airport ground equipment fails in operations to enhance failure prediction, reduce maintenance and costs. Airports are essential to enhance the economy of a developing country and these failures affect the efficiency of the airport system. Consequently, this paper deals with utilising the risk priority number of equipment failures to create ranks for selected airport ground equipment and study the performance of this equipment using the grey relational analysis. Three methods were established to evaluate the failures of five selected major equipment (elevators, travellator, escalator, baggage handling equipment and air-conditioners): the risk priority number (RPN), RPN with same weights and RPN with different weights for the risk factors. All the methods approved elevator 8, travellator 6, escalator 11, baggage handler 3 and air conditioner 9 as the best, indicating reduced risk factors from the equipment. The worst equipment approved by all the methods are elevator 2, baggage handler 6 and air-conditioner 7. However, while the RPN, and RPN (with an equal weight of risk factors) approve travellator 3 and escalator 9 as the worst equipment, a divergent choice of travellator 1 and escalator 5 is mapped RPN method with different weights for the risk factors as the worst equipment. This work contributes to the airport maintenance literature by applying three models to evaluate the failure of ground equipment in airports to identify equipment that should be given the utmost priority and those that warrant the least attention of the airport maintenance management.

Keywords: Prioritisation, mechanical equipment, airport, aerospace industry, customer service

1 Introduction

Airports in sub-Saharan African countries prioritise excellence in customer service to sustain their continued operations in the face of dwindling economic fortunes in the aerospace industries [1-3]. Traditionally, safety and maintenance of ground equipment which services customers on arrival and departure locations, in the airport, have been the backbone of excellent customer service in the airport [4, 5]. However, the presence of hazards and equipment downtime has constrained the capacity of airports to offer adequate and excellent ground mechanical equipment service to passengers [6, 7]. Consequently, the management of airports and researchers are increasingly promoting safety and effective maintenance of ground mechanical equipment [8, 9]. These activities communicate and support the improvement of safety performance and avoid disrupting service [8, 9].

Moreover, flight passengers in airports are expected to experience superior flight customer service and this experience begins and ends at the airports [3, 6]. While awaiting flights or on arrival from a flight, passengers spend enormous time in the airport and some comfort is expected from the available ground equipment as passengers move through the airport and at the terminal hall [6]. Unfortunately, many airports have poorly implemented maintenance schedules, opening up costly damages to the ground equipment and exposing both passengers and staff of the airport to hazards, which may cause accidents. Therefore, the identification of key failures and trends of ground equipment is crucial for effective maintenance [8]. Consequently, understanding and assessing when the ground equipment would fail is an important issue which should be given utmost attention for improved operational efficiency in airports [8, 10, 11-20]. Currently, in airport maintenance management, enough ground equipment failure information is not frequently available to the maintenance managers and this issue continues to expand with an increase in demand for airport services.

Ground equipment such as air conditioners, baggage handling equipment, vary in age, capacity, usage levels, and the number of maintenance tasks carried out on them. There are no scientific means of even deciding their failure performance; how much time the machine must fail despite the utmost maintenance attention is not known. This research gap motivates the present investigation to pursue an assessment of the failure behaviour of ground equipment in a case airport. Consequently, the purpose of this paper is to analyse the failure performance of major airport ground equipment using the failure modes effects analysis (FMEA) [21-25] with the grey relational analysis. To achieve this, three methods were developed and used to analyzed the airport ground equipment, namely the risk priority number (RPN) method [8, 10], the grey-RPN with equal weights of the risk factors and the grey-RPN with unequal weights of the risk factors. Five major pieces of equipment were used in the study, namely the elevator, escalator, travellator, baggage handling equipment and air conditioners. For each piece of equipment, the total number in varying capacities and locations within the airport was considered in the analysis. The failure modes of each piece of equipment were assessed based on expert's opinion, handbooks and manuals on these pieces of equipment from the manufacturers.

The application of the three methods yielded ranks, RPN, and grey-RPN values. Ranks provided the most important to the least important failure of the machine and these are varied for each piece of equipment. To evaluate the maximum possible failure of the equipment, the top three failures were identified and matched to the three methods in an eigenvalue determination approach using the matrix method. The determinant of the difference between the three by three matrix containing the topmost failures and the corresponding values of the methods was noted against the product of the lambda and the identity matrix to yield a polynomial of the maximum power of three. The final values were however obtained from these. The eigenvalues of this linear operator on a linear space were determined. The eigenvalues are the highest possible failure level. The principal advantages of the methods include assured effective preventive maintenance planning, minimization of cost, enhanced throughout and minimized equipment downtime.

Briefly mentioned, the survey of airport maintenance literature reveals a prospect to develop a study involving the following scope:

1. An airport field study that exposes ground equipment failures in the developing country context.

2. The choice of ground equipment has limits to escalators, elevators, travellators, baggage handling equipment and air conditioners
3. Failure modes effects and criticality analysis and grey relational analysis are employed as tools for failure assessment.

2 Material and Methods

2.1 Justification for the choice of equipment

In the airport system, there are several categories of ground support equipment. Some of these are luggage trolleys, airport passenger boarding bridges, runway, sweeper, automated aircraft washing, robots, towing tractors, ground power units, elevators, escalators, travelators, air-conditioners and baggage handling equipment (Fig. 1).

However, a problem confronted in this study is to choose the most important equipment with which efforts can be concentrated to reduce failures and enhance their service performance customers. This section provides the essential details to justify the choice of the equipment analyzed in this study. In an airport, the failure of air-conditioners, for example, in the waiting hall is a leading passenger discomfort criterion. Airport air-conditioning system failure in airport terminal buildings may cause major discomfort to passengers. This prompts the maintenance crew and contractors to work in mitigating the effects and repair the cooling system failure. This failure may be due to chiller motors having stopped operating. With failures, temperatures in the building become high and immediate efforts by airport staff may be the use of fans and dehumidifiers to make the airport terminal more comfortable to passengers. To strengthen the choice of the air conditioner as important in the air transport system, looking beyond the terminal one may consider a planes air-conditioner not working. This failure makes breathing difficult for passengers and the pilot may be constrained to ground the plane for passenger safety.

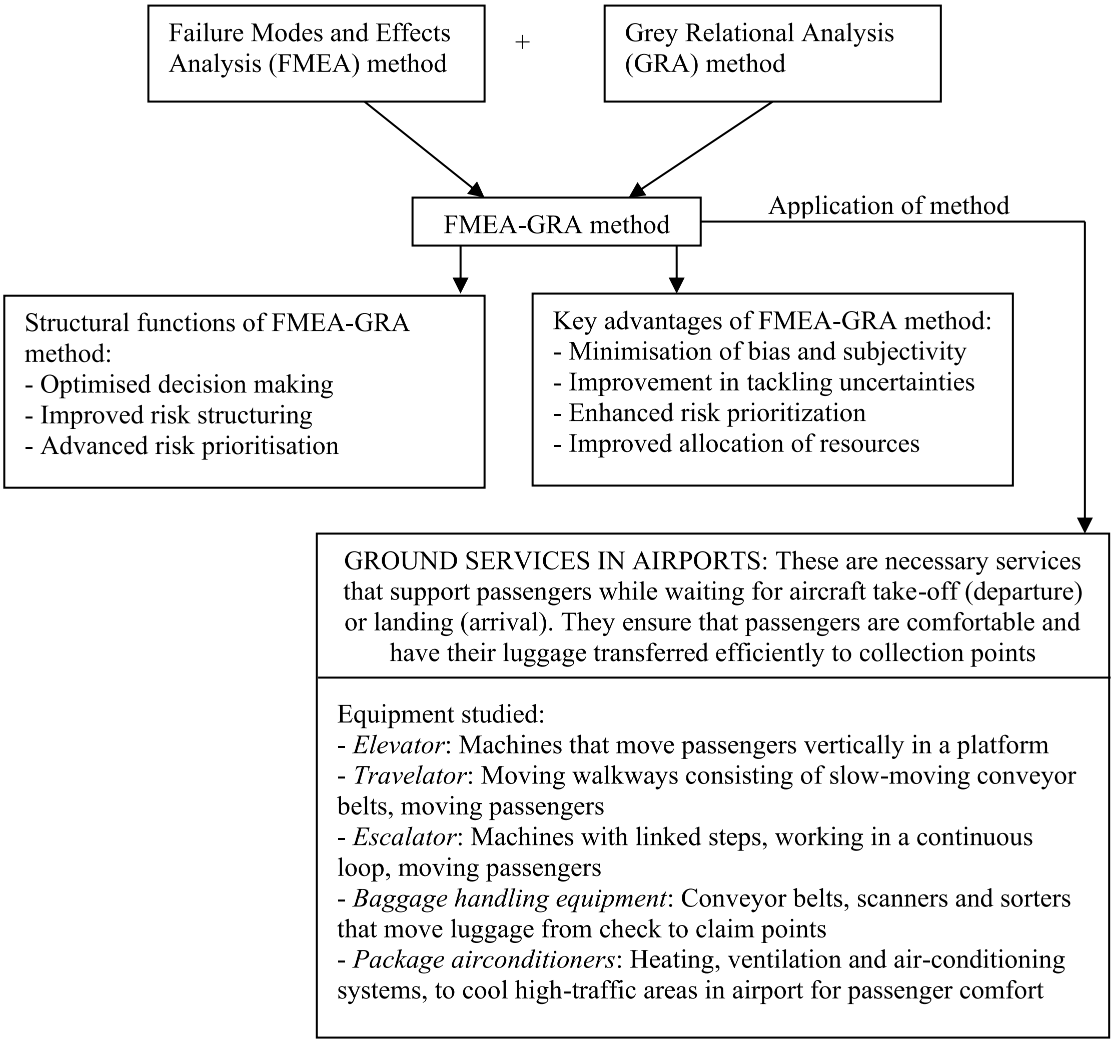

Figure 1. The FMEA-GRA method and its application to ground services in airports

2.1.1 Air-conditioner

While establishing a portfolio of essential equipment for an airport's ground equipment, the choice of the air-conditioner is a substantial decision. In this instance, important issues such as the following should be considered; the size of the room/hall to be cooled, capacity and physical size of the air-conditioner, the type of air-conditioner, (maybe split, floor standing or others), power requirements, condensate channelling control, location of outdoor unit/cross ventilation, spare parts availability, protection system/phase failure and sequence control, number of air-conditioners required, hours of operation per day, equipment/persons to serve, estimated years of use, location of the emergency control system, cooling coil make, (copper or aluminium for split air-conditioners), blowers and quantity as well as compressors and quantity while considering bigger units. The choice of air-conditioner as key ground equipment is important because it offers uncompromising service quality levels to passengers awaiting departure to destinations or arriving from a place. Terminal halls require strong air conditioners to ascertain superior comfort to passengers' all-the-year-round. Air-conditioners are key equipment responsible for controlling the energy efficiency of the airport and the use of drillers and heat pumps with energy-efficiency designs guarantees the attainment of energy efficiency in airports. With today's technology, it is possible to use air-conditioners attached with an integrated heat recovery system to minimize waste energy consumption.

2.1.2 Baggage handling equipment

This is a kind of conveyor arrangement at an airport that serves three principal functions. First, it moves travellers' bags from the inspection area to the exit area. Second, it runs the travellers' bags from gates to gates while transferring loads. Third, it runs the travellers' bags from the entrance gate to the baggage receiving area. Consequently, understanding the failure attributes of the baggage handling equipment is a crucial factor while deciding on the failure assessment of critical airport ground equipment. The reason is that a properly functioning baggage handling equipment has a direct effect in maintaining the happiness of customers. It is influential in attracting travellers to an airport, maintaining the main airline hub where a focal linkage point from which several flights regarding a specific airline may be routed. The baggage handling equipment is often assessed on the movement of bags from one point to another at the speed of the travellers. Slow-moving bags keep travellers frustrated as they want for their bags at each point; bags may fail to make the linking flights on if too slow. Also when the bags are too fast in movement, they may make the linking flights which passenger misses. However, with a failed baggage handling system, its unavailability many warrant the airport using less effective carriage systems, leaving the customers frustrated.

2.1.3 Elevator

The elevator in an airport is a piece of substantial equipment for ground movements which should be considered while analysing equipment failures of critical ground equipment in airports. The reason is that it makes it practical for travellers to move about at the airport terminal, making travels by air accessible and comfortable to handicapped people. The failure of the control system, which determines the direction of the movement of the elevator and the safety systems for the prevention of catastrophes may leave the travellers unhappy particularly those with disabilities. Thus, failure analysis phenomenon such as the failure modes effects and criticality analysis may be important to understand the failures of the elevators and improve their service qualities.

2.1.4 Escalator

In the scheme to choose key ground equipment in the airport for analysis there is scope to include the escalator. It is largely expensive ground equipment in the airport, a variation of the conveyor belt. It works as a pair of moving chain loops draws a set of stairs regularly, thereby moving many travellers for a short distance at a relatively acceptable speed. However, a deep knowledge of the failure mechanism for escalators is required in a drive for lean maintenance where many failures are predicted before occurrence and maintenance cost minimum. Including escalator in the equipment list to analyse for failures brings maintenance of the airport cheaper in the long run as escalators hold a major investment and repair cost in airports.

2.1.5 Travellators

Travellators are imperative ground equipment, which should be included in choosing the key ground equipment whose failures are to be analysed in an airport. The airport maintenance manager often displays eagerness on when a failed travellator will be working "as-good-as-new" after repairs to make travellers happy in their travelling experience. Travellators, also known as moving-walkways, is essential as the traveller moves around the airport. Persistent movement interruptions of the traveller by the travellator influences the average downtime cost of maintaining the travellators and their manning staff lifespan in service and the overall facility condition.

Moreover, the risk priority evaluation through application of FMECA combined with grey relational analysis was intended for analysis of performance of select mechanical equipment within the airport setting of a developing country. However, the majority of malfunction assessment was controlled by the need to have improved as well as significant accessibility and dependability of components in order to guarantee effective sustenance processes. In achieving the above, a mathematical technique in support of recognizing and analyzing probable malfunctions was employed by utilizing failure mode effects and criticality analysis (FMECA) and grey relational analysis. The FMECA method integrated with the Grey Relational Analysis is executed by the following algorithms:

Step 1: Determination of standard (reference) series: target series, known as the standard series, of length R is as follows [10]:

$$Y_o = \{Y_o(1), Y_o(2), \ldots, Y_o(R)\} \quad (1)$$

Standard series are determined by taking the smallest value of all risk factors, since small values denote smaller risk

$$Y_o = \{Y_o(1), Y_o(2), \ldots, Y_o(R)\} = \{1, 1, \ldots, 1\} \quad (2)$$

Step 2: Determination of comparative series – h information series related to the occurrence, severity and detectability of failure is stated thus [10]:

$$Y_i = \{Y_i(1), Y_i(2), \ldots, Y_i(R)\} \quad i = 1, 2, \ldots, h \quad (3)$$

$Y_i(R)$ represents the R^{th} factor of Y_i.

To compare all information series, g information series is defined as in the following matrix

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_g \end{bmatrix} = \begin{bmatrix} Y_1(1) & Y_1(2) & \cdots & Y_1(R) \\ Y_2(1) & Y_2(2) & \cdots & Y_2(R) \\ \vdots & \iddots & \ddots & \vdots \\ Y_g(1) & Y_g(2) & \cdots & Y_g(R) \end{bmatrix} \quad (4)$$

Step 3: Obtaining the distance between standard series and comparative series and calculating the coefficient value. All the three risk parameters are compared with the standard series for each failure series, and the relation coefficient is given by the following equation [10]:

$$\beta\left(Y_o(R), Y_j(R)\right) = \frac{\Omega_{\min} + (\theta\Omega_{\max})}{\Omega_{oj}(R) + (\theta\Omega_{\max})} \quad (5)$$

Where $j = 1, 2, ..., h$ and $R = 1, 2, ..., g$

$Y_o(R)$ is the standard series and $Y_j(R)$ is the comparative series.

$$\Omega_{\min} = \min_{\forall j \in i} \min_{\forall R} \left\| Y_o(R) - Y_j(R) \right\| \quad (6)$$

$$\Omega_{\max} = \max_{\forall j \in i} \max_{\forall R} \left\| Y_o(R) - Y_j(R) \right\| \quad (7)$$

θ is defined as a coefficient between $(0,1)$ but in order to reduce the effect of the maximum value on the relationship coefficient, θ is usually taken as 0.5. The aim of introducing this coefficient is to adjust the difference between $\Omega_{oj}(R)\, and\, \Omega_{\max}$.

Step 4: Determination of the grey relationship degree – This is measure of the geometric relationship between standard series and comparative series. If the two series are compared to be the same, then the grey relationship degree is equal to 1. The grey relationship degree indicates the degree of relationship between compared and standard series [10].

$$\lambda\left(Y_o, Y_j\right) = \frac{1}{g} \sum_{R=1}^{g} \beta\left(Y_o(R), Y_j(R)\right) \quad (8)$$

g = decision factor number

If the weights of each criterion are given, the grey relationship degree can be calculated by multiplying the grey relationship coefficient of the criterion and weight values of the degree magnitude of the criterion.

$$\lambda\left(Y_o, Y_j\right) = \sum_{R=1}^{g} \beta\left(Y_o(R), Y_j(R)\right) F_R \quad (9)$$

F_R is the weighting coefficient of the factors.

$$\sum_{R=1}^{g} F_R = 1 \quad (10)$$

Step 5: Rating the risk priorities – The factor series with the highest grey relationship degree denote the best alternative in decision making problems. This is to say that if

$\beta(Y_o, Y_i) \geq \beta(Y_o, Y_j)$, then the relationship between $Y_i \, and \, Y_o$ is greater than the relationship between $Y_j \, and \, Y_o$.

3 Results and Discussions

In section 2, the methodology of the grey relational analysis was defined in mathematical terms was observed as a complementary method for the failure modes effects and criticality analysis and has the potential of providing substantial information about the equipment failures and at the same time capable of performing in a situation where incomplete information surrounds the problem to solve. Data was collected from the records of the airport used for the study, located in a major city of a sub-Saharan African country. The declaration of the source of data is not made since the arrangement for the release of the data was based on the researcher maintaining confidentiality of the data. The airport ground service is maintained by an indigenous ground handling contractor servicing the airport. The company provided the essential data for this analysis. The collected data are on passenger handling services, ramp handling services, cargo handling services and baggage handling services. In this paper, the authors have streamlined choice to five pieces of equipment. Scoring of the RPN parameters was done by one of the authors, an expert in maintenance. The researcher who serves as the expert that provided scores for the present study has a bachelor's and master's degrees in mechanical engineering and is currently pursuing a doctoral degree in a Nigerian University in the area of maintenance engineering. Coupled with more than 5 years of experience in maintenance planning and execution in an airport, the researcher has valuable experience to assess the handling facilities of the ground services in the airport.

3.1 Scoring criteria

The scoring criteria adopted in this study are derived from the FMEA method and are referred to as the risk priority number (RPN) for ground service handling equipment. The RPN quantitatively assesses the risk involved in managing the ground support equipment. A risk number is assigned to the service function of the handling equipment, which is a part of a failure modes and effects analysis. In this paper, one of the authors is a senior maintenance personnel member at the studied airport, whose principal function includes the maintenance of handling equipment, the scope of which is covered in the present study. The long-term experience of the author as maintenance personnel has been deployed to assign the RPN based on an established criterion of evaluating the severity of impact, S, frequency of occurrence, O, and likelihood of detection, D. Severity rates how critical the passenger to an airport will perceive the effect of a failed handling equipment. Passengers are concerned with their time wasted, risks to their belongings and inconvenience caused to them by a failed handling equipment. Severity may be heightened when the broken-down handling equipment causes broken or damaged belongings, lost luggage or mistracked belongings. Eventually, anxiety and stress develop for the passenger whose travel plans may be disrupted. Occurrence is another critical issue, which estimates the likelihood that the cause of a particular failure will occur. For example, a flaw in the design of the handling door for an elevator, which could cause failure, could be assigned a high occurrence based on past issues. However, a new landing door that has not yet tested in operation might show a low occurrence. The occurrence rating is often evaluated at the designed life of the landing door, for example. Detection estimates how effective control acts to detect or prevent failure modes before the passenger experiences them. The scoring criteria for the baggage handling activities place personal injury as overriding and focus on the maintenance effectiveness of the ground service equipment. In general, all three risk priority factors, S, O and D were measured based on a scale of 1 to 10. These factors have their scoring criteria discussed as follows:

1. Severity: Severity is represented by the letter S, and evaluates the failure impact on passengers. The following are the appropriate scores under severity:
   10 (Mishap): Equipment malfunctions, causes equipment damage, injure workers, and result in costly delays.
   7-8 (Excessive): Major service disruptions, handling equipment out-of-service.
   4-6 (Moderate): Moderate disruption of handling services, 2-3 (Low): Minor inconvenience to passengers.
   1 (Negligible): No noticeable influence on handling activities.

2. Occurrence: Occurrence is represented as O, states the failure frequency, commonly oriented towards preventive maintenance data. The following are the appropriate scores under occurrence:

   9-10 (Profound): Repeated, exceeds once in 20 cycles.

   7-8 (Excessive): Failure occurring, once in 20 to 100 cycles

   4-6 (Moderate): Periodic failures, once in 100 to 1000 cycles

   2-3 (Low): Infrequent failures

   1: (Remote): Unlikely failures, less than once in 10,000 cycles.

3. Detection: Detection is represented as letter D, declares the ability of installed equipment controls, such as electronic sensors or even physical inspections, to establish the faults before being activated. The following are the appropriate scores under detection:

   9-10 (Very low): No installed control or experienced maintenance team members to detect failure before it occurs.

   7-8 (Low): The possibility of detecting failure before starting the handling equipment is low.

   4-6 (Moderate): The faults can be detected on a moderate chance, such as when daily pre-operational checks on handling equipment are made.

   2-3 (Excessive): The likelihood of detecting failure through the installed maintenance system is high.

   1 (Expected): Installed preventive controls will certainly detect possible failure.

3.2 RPN calculations and interpretation of results

RPN can range from 1 to 1,000, where 1 indicates the lowest risk, and 1,000 indicates the highest risk. A higher risk priority number signifies a higher priority risk that needs immediate attention. Applying the RPN philosophy in airport ground service in failure mode is a numerical approach to focus scarce maintenance resources on the most critical risks. This prioritisation supports handling quality control in airports, passenger satisfaction and handling operational efficiency of passenger luggage. In between these two extreme values of 1 and 1000 are four broad classifications, stated as follows:

- Critical Risk (RPN > 500): The system manager needs to take immediate mandatory steps to mitigate the operation.
- High Risk (RPN 300 – 500): Prioritise activities and engage in prompt action to stop failure.
- Moderate Risk (RPN 100 -300): It is essential to act within a reasonable time frame.
- Low Risk (RPN 1- 100): Need to monitor the service process but may not require immediate action.

From the computations of the RPN score, the researcher implements corrective actions targeting the highest RPN first. The higher the RPN, the more serious the handling equipment failures and the easier it is to detect such failures. Improvement efforts are directed at places where they are needed most.

3.3 The raw values for RPN components

The raw values for RPN components are shown in Table 1A and Table 1B in the Appendix. Consider the raw values of the elevator in Table 1A. In this section, the researcher wants to calculate the risk priority number for 10 potential failures of the elevator at the airport. The researcher, an experienced maintenance professional, assigns ratings of 1 to 10 based on the scoring criteria discussed in this paper, for each of the 3 categories of probability of occurrence, severity of failure and probability of an escape from being detected. The aim is to determine which of the 10 failure scores has the highest RPN. For the first failure, "Elevator Car", the product of O, S and D is 16. Other failure modes in the elevator are computed (Table A), and the observed highest value is 729. The same procedure was followed for other equipment, and the detailed calculations are shown in Tables 1A and 1B. It is shown that travellator, escalator, baggage handling equipment and package air conditioners have the highest values of 648 (controller), 648 (controller), 135 (controller), and 280 (power circuit board), respectively. These are the most important components of all the systems, which should be given the topmost attention. However, this analysis uses the traditional RPN scale, which is a benchmark to compare the novel methods proposed in this work. The novel method integrates the grey relational analysis with the RPN, giving it unique and robust results shown in the other points of this work.

The information series matrix below is obtained by utilizing the RPN values (Risk Ranking Table for Elevator) so as to evaluate the comparative series.

$$\begin{bmatrix} Y_1(1) & Y_1(2) & Y_1(3) \\ Y_2(1) & Y_2(2) & Y_2(3) \\ Y_3(1) & Y_3(2) & Y_3(3) \\ Y_4(1) & Y_4(2) & Y_4(3) \\ Y_5(1) & Y_5(2) & Y_5(3) \\ Y_6(1) & Y_6(2) & Y_6(3) \\ Y_7(1) & Y_7(2) & Y_7(3) \\ Y_8(1) & Y_8(2) & Y_8(3) \\ Y_9(1) & Y_9(2) & Y_9(3) \\ Y_{10}(1) & Y_{10}(2) & Y_{10}(3) \end{bmatrix} = \begin{bmatrix} 1 & 8 & 2 \\ 1 & 8 & 1 \\ 1 & 8 & 1 \\ 8 & 7 & 1 \\ 3 & 7 & 2 \\ 3 & 7 & 2 \\ 2 & 8 & 2 \\ 9 & 9 & 9 \\ 2 & 7 & 2 \\ 2 & 7 & 2 \end{bmatrix}$$

The difference matrix is given below:

$$\begin{bmatrix} \Omega_1(1) & \Omega_1(2) & \Omega_1(3) \\ \Omega_2(1) & \Omega_2(2) & \Omega_2(3) \\ \Omega_3(1) & \Omega_3(2) & \Omega_3(3) \\ \Omega_4(1) & \Omega_4(2) & \Omega_4(3) \\ \Omega_5(1) & \Omega_5(2) & \Omega_5(3) \\ \Omega_6(1) & \Omega_6(2) & \Omega_6(3) \\ \Omega_7(1) & \Omega_7(2) & \Omega_7(3) \\ \Omega_8(1) & \Omega_8(2) & \Omega_8(3) \\ \Omega_9(1) & \Omega_9(2) & \Omega_9(3) \\ \Omega_{10}(1) & \Omega_{10}(2) & \Omega_{10}(3) \end{bmatrix} = \begin{bmatrix} 0 & 7 & 1 \\ 0 & 7 & 0 \\ 0 & 7 & 0 \\ 7 & 6 & 0 \\ 2 & 6 & 1 \\ 2 & 6 & 1 \\ 1 & 7 & 1 \\ 8 & 8 & 8 \\ 1 & 6 & 1 \\ 1 & 6 & 1 \end{bmatrix}$$

From the difference matrix, $\Omega_{\min} = 0, \Omega_{\max} = 8$

$$\beta(Y_o(R), Y_j(R)) = \frac{\Omega_{\min} + (\theta\Omega_{\max})}{\Omega_{o1}(1) + (\theta\Omega_{\max})} = \frac{0 + (0.5 \times 8)}{0 + (0.5 \times 8)} = 1$$

For $\Omega_1(2)$,

$$\beta(Y_o(R), Y_j(R)) = \frac{\Omega_{\min} + (\theta\Omega_{\max})}{\Omega_{o1}(2) + (\theta\Omega_{\max})} = \frac{0 + (0.5 \times 8)}{7 + (0.5 \times 8)} = 0.36$$

In like manner, for $\Omega_1(3)$ $\beta_1(3) = \frac{0 + (0.5 \times 8)}{1 + (0.5 \times 8)} = 0.8$

$\beta_2(1) = 1$, $\beta_2(2) = 0.364$, $\beta_2(3) = 1$

$\beta_3(1) = 1$, $\beta_3(2) = 0.364$, $\beta_3(3) = 1$

$\beta_4(1) = 0.364$, $\beta_4(2) = 0.4$, $\beta_4(3) = 1$

$\beta_5(1) = 0.667$, $\beta_5(2) = 0.4$, $\beta_5(3) = 0.8$

$\beta_6(1) = 0.667$, $\beta_6(2) = 0.4$, $\beta_6(3) = 0.8$

$\beta_7(1) = 0.8$, $\beta_7(2) = 0.364$, $\beta_7(3) = 0.8$

$\beta_8(1) = 0.333$, $\beta_8(2) = 0.333$, $\beta_8(3) = 0.333$

$\beta_9(1) = 0.8$, $\beta_9(2) = 0.4$, $\beta_9(3) = 0.8$

$\beta_{10}(1) = 0.8$, $\beta_{10}(2) = 0.4$, $\beta_{10}(3) = 0.8$

$$\begin{bmatrix} \beta_1(1) & \beta_1(2) & \beta_1(3) \\ \beta_2(1) & \beta_2(2) & \beta_2(3) \\ \beta_3(1) & \beta_3(2) & \beta_3(3) \\ \beta_4(1) & \beta_4(2) & \beta_4(3) \\ \beta_5(1) & \beta_5(2) & \beta_5(3) \\ \beta_6(1) & \beta_6(2) & \beta_6(3) \\ \beta_7(1) & \beta_7(2) & \beta_7(3) \\ \beta_8(1) & \beta_8(2) & \beta_8(3) \\ \beta_9(1) & \beta_9(2) & \beta_9(3) \\ \beta_{10}(1) & \beta_{10}(2) & \beta_{10}(3) \end{bmatrix} = \begin{bmatrix} 1 & 0.364 & 0.8 \\ 1 & 0.364 & 1 \\ 1 & 0.364 & 1 \\ 0.364 & 0.4 & 1 \\ 0.667 & 0.4 & 0.8 \\ 0.667 & 0.4 & 0.8 \\ 0.8 & 0.364 & 0.8 \\ 0.333 & 0.333 & 0.333 \\ 0.8 & 0.4 & 0.8 \\ 0.8 & 0.4 & 0.8 \end{bmatrix}$$

Grey relationship degree (Grey RPN) for each failure mode with assumption that all three risk factors have equal weights is calculated thus from Equation (8):

$$\lambda(Y_1, Y_3) = \frac{1}{3}(1 + 0.364 + 0.8) = 0.721$$

With the same process applied to other failure mode:

$$Grey\ RPN = \begin{bmatrix} 0.721 \\ 0.788 \\ 0.788 \\ 0.588 \\ 0.622 \\ 0.622 \\ 0.655 \\ 0.333 \\ 0.667 \\ 0.667 \end{bmatrix}$$

Calculation of Grey relationship degree (Grey RPN) with the assumption that the risk factors have different weights using Equation (9):

Taking $\sum_{R=1}^{g} F_R = 1$, the weight coefficients for the occurrence, severity and detectability of the failure were taken as $F_O = 0.4$, $F_S = 0.4$, $F_D = 0.2$ respectively.

$$\lambda(Y_1, Y_3) = \{(1 \times 0.4) + (0.364 \times 0.4) + (0.8 \times 0.2)\} = 0.706$$

With the same process applied to other failure modes

$$Grey\ RPN = \begin{bmatrix} 0.706 \\ 0.746 \\ 0.746 \\ 0.506 \\ 0.587 \\ 0.587 \\ 0.626 \\ 0.333 \\ 0.640 \\ 0.640 \end{bmatrix}$$

Table 1. RPN Values for Elevator

Elevator No.	Failure modes	RPN	Ranking	Grey RPN* weight	Ranking	Grey RPN** weight	Ranking
1	8	16	8	0.721	8	0.706	8
2	10	8	10	0.788	10	0.746	10
3	9	8	9	0.788	9	0.746	9
4	2	56	2	0.588	2	0.506	2
5	4	42	4	0.622	4	0.587	4
6	3	42	3	0.622	3	0.587	3
7	5	32	5	0.655	5	0.626	5
8	1	729	1	0.333	1	0.333	1
9	6	28	6	0.667	6	0.64	6
10	7	28	7	0.667	7	0.64	7

Note: *Risk factors have equal weights, ***Risk factors have equal different weights

Table 1 shows the results of three methods, namely the RPN, grey RPN with risk factor having equal weights and grey RPN with risk factors having different weights. For the first method, RPN, the highest and the least values are 729 and 8, correspondingly. The meaning is that keeping equipment 8 in service demand substantial risk values and if captured the whole system would run smoothly. Corresponding to elevator equipment 8 is the first rank for the RPN method. By tracing it to the other two methods, elevator 8 maintains the first position in both the grey RPN with equal risk factor weights, sharing grey values of 0.333 for each of these two methods. Table 1 also reveals the worst values for the three methods. It was elevator 2 for the three methods having the RPN of 8, grey RPN with an equal risk factor of 0.788 and grey RPN with an unequal risk factor of 0.746. Having done this analysis, the authors are interested in what causes the poor performance. It was observed that several causes may be responsible for the faults but some faults keep occurring all the time. This is referred to as the significant faults for the elevator. Four key faults were identified, namely the controller, landing door, car buffer and counterweight tension pulley arranged in order of importance. Consequently, efforts to reduce these faults will lead to the enhanced productivity of the equipment and the overall quality of service of all elevators in the system.

Table 2. RPN Values for Travelator

Travelator No.	Failure modes	RPN	Ranking	Grey RPN* weight	Ranking	Grey RPN** weight	Ranking
1	8	48	8	0.603	8	0.650	11
2	4	112	4	0.521	4	0.466	4
3	11	28	11	0.667	11	0.640	10
4	7	56	7	0.588	7	0.633	8
5	3	512	3	0.364	3	0.364	3
6	1	648	1	0.343	1	0.345	1
7	10	28	10	0.667	10	0.640	9
8	6	72	6	0.566	6	0.546	5
9	9	30	9	0.656	9	0.627	7
10	5	112	5	0.521	5	0.553	6
11	2	576	2	0.354	2	0.358	2

Note: *Risk factors have equal weights, ***Risk factors have equal different weights

By following through the same steps from the establishment of the information series index to the summary of results from the elevator to obtain Table 1, Table 2 is obtained for travelator. Table 2 shows the result using the three methods of RPN, grey RPN with equal risk factor weights and grey RPN with unequal risk factor weights when travellator is considered. For the first method, RPN, the highest and the least values are 648 and 28, respectively. This means that keeping the travellator 6 in service demands substantial risk value and efforts to capture it should be topmost for this travellator 6. By tracing the positions for the other two methods, travellator 6 still retain the best values, with the grey RPN of 0.343 and 0.345, respectively, for grey RPN with an equal weight of cycle factor and grey RPN with an unequal weight of risk factors, respectively. Benchmarked against the elevator, for the RPN method, the performance of the best travellator is worse than the best of the elevator by 11.1%. For the grey RPN with an equal weight of risk factors, the best travellator is better than the equivalent best elevator by 1%. For the grey RPN with an unequal weight of risk factors, best travellator is better than the best elevator by 3.6% for the worst cares, for the RPN methods, the best performance of the travellator exceeds the performance of the best elevator by 250%. The grey RPN with an equal weight of risk factor and grey RPN with an unequal weight of risk factor were used to select the best values for the travellator and compared with the best values of the elevator, it was known that they were worse by 15.36% and 14.21%, respectively. A similar procedure conducted for elevator is extended to escalator, Table 3.

Table 3 shows the results of the three methods, for the first method, RPN, the highest and the least values are 648 and 28, correspondingly for the escalators 11 and 9. By tracing the position for the other two methods, escalator 11 retains the first position for the grey RPN with an equal weight of risk factors having a value of 0.343 and for the same method, the worst values have retained an elevator 9 with a value of 0.667. For the third methods, the best escalator is escalator 11, having a value of 0.345 while the worst escalator is escalator 5 having a value of 0.650.

3.4 Benchmarked against the performance of elevators having the best and worst performance

We consider the first method, the RPN. The performance grew by 11.1% when the best escalator was compared with the best elevator. However, when the best escalator was compared with the best elevator using the grey RPN_E, the performance dropped by 3%. When the best escalator was compared with the best elevator using RPN (with an equal weight of risk factors), the performance dropped by 3.6%.

Table 3. RPN Values for Escalators

Escalator No.	Failure modes	RPN	Ranking	Grey RPN* weight	Ranking	Grey RPN** weight	Ranking
1	4	128	4	0.509	4	0.451	4
2	6	64	6	0.576	6	0.618	7
3	8	48	8	0.610	8	0.572	6
4	5	126	5	0.511	5	0.547	5
5	7	48	7	0.603	7	0.650	11
6	9	30	9	0.656	9	0.627	8
7	3	512	3	0.364	3	0.364	3
8	10	28	10	0.667	10	0.640	9
9	11	28	11	0.667	11	0.640	10
10	2	567	2	0.355	2	0.360	2
11	1	648	1	0.343	1	0.345	1

Note: *Risk factors have equal weights, ***Risk factors have equal different weights

Table 4. RPN values for baggage handling equipment

Baggage equipment No.	Failure modes	RPN	Ranking	Grey RPN* weight	Ranking	Grey RPN** weight	Ranking
1	8	24	8	0.677	8	0.612	7
2	10	14	10	0.733	10	0.720	10
3	1	135	1	0.426	1	0.422	1
4	5	48	5	0.610	5	0.599	5
5	6	42	6	0.622	6	0.613	8
6	11	6	11	0.815	11	0.778	11
7	7	36	7	0.637	7	0.604	6
8	4	54	4	0.600	4	0.560	4
9	9	24	9	0.681	9	0.658	9
10	3	96	3	0.536	3	0.483	3
11	2	108	2	0.526	2	0.471	2

Note: *Risk factors have equal weights, ***Risk factors have equal different weights

For the worst performance, when the worst performance of elevator was compared with the worst performance of the elevator, the performance dropped by 250%. For the second method, grey RPN with equal weight improved by 15.4%. For the third method, grey RPN with an unequal weight of the risk factors, the performance improved by 12.9. Table 4 shows the result of the three methods when the baggage handling equipment is considered. Again, the procedure used to obtain summarized results for the elevator in Table 1 is applied to obtain Table 4. The best baggage handling equipment was equipment 3 when the RPN method is considered. It displays a value of 135 as the RPN while the worst equipment was identified as equipment 6 with a value of 6. Using the grey RPN with equal risk weights factors, the best equipment was chosen as equipment 3 with a value of 0.425. However, for the worst equipment, equipment 6 was identified with a grey value of 0.815. Furthermore, using the grey RPN with unequal weight of the risk factors, baggage handling equipment 3 was chosen as the best with a grey value of 04.22. However, the worst performance was attributed to equipment 6 with a grey value of 0.778. By comparing the results of the best and worst-performing equipment of the benchmark of the best and worst-performing elevators, the following may be discussed for the RPN method, the best performing equipment improved by 81.5%. however, for the grey RPN with equal risk factor weights and grey RPN with unequal risk factor or weights, the performance of the best performing equipment dropped by 27.9% and 26.7%, respectively. For the worst values, there is an enhance mention performance when the RPN method is used, obtained as 25%. However, for the grey-RPN_E and grey-RPN_D, the worst values declined respectively by 3.4% and 4.3%. Also, following the steps taken to obtain Table 1, Table 5 was obtained.

Table 5 shows the result of the three methods. For the first method, RPN, the highest and least values are 280 (air conditioner 9) and 3 (air conditioner 3). For the grey RPN with equal weights, the best and then worst equipment are air-conditioner 9 (0.421) and air-conditioner 7 (0.889), respectively. for the grey RPN with unequal weights, the best and the worst equipment are air conditioner 9(0.426) and air conditioner 7 (0.867), respectively. By comparing the results of the best and worst-performing equipment of the air conditioner and the benchmark of the best and worst-performing elevators, the following may be established. For the RPN method, the best performing equipment improved by 61.6%. nonetheless, for the grey RPN with equal risk factor weights and grey RPN with unequal risk factor weights, the performance concerning the best performing equipment reduced by 26.4% and 27.9%, respectively. For the worst values, there is an enhancement in performance when the RPN method is used, obtained as 62.5%. Nonetheless, for the grey RPN with equal weights of risk factors, the worst values declined respectively by 12.8% and 16.2%.

Table 5. RPN values for air conditioners

Air conditioner No.	Failure modes	RPN	Ranking	Grey RPN* weight	Ranking	Grey RPN** weight	Ranking
1	4	108	4	0.526	4	0.542	4
2	5	70	5	0.567	5	0.580	5

3	8	40	8	0.621	8	0.646	8
4	7	40	7	0.621	7	0.646	7
5	9	40	9	0.621	9	0.646	9
6	3	120	3	0.505	3	0.506	3
7	12	3	12	0.889	12	0.867	12
8	2	144	2	0.492	2	0.501	2
9	1	280	1	0.421	1	0.426	1
10	10	28	10	0.633	10	0.660	10
11	6	48	6	0.603	6	0.634	6
12	11	25	11	0.667	11	0.700	11

Note: *Risk factors have equal weights, ***Risk factors have equal different weights

3.5 Benchmarked with travellator as the base performance equipment

For a comprehensive evaluation of the performance of the best equipment, the performance obtained for each of the pieces of equipment was compared with the travellator. The following results were obtained. For the RPN method, the comparative best performance of the elevator, escalator, baggage handling equipment and air-conditioners to travellator is 112.5%, 100%, 20.8% and 43.2%, respectively. For the grey RPN with equal weight for the risk factors, concerning elevator, escalator, baggage handling equipment and air-conditioners relative to travellator, the best performance is 97.1%, 100%, 124.2% and 122.7%, respectively. For the grey-RPN with an unequal weight of the risk factor, the elevator, escalator, baggage handling equipment and air-conditioner relative to the best performing travellator are 96.5%, 100%, 22.3%, 123.5%, respectively.

Concerning the worst performance, for the RPN method, concerning the elevator, escalator, baggage handling equipment, and air-conditioner, relative to the travellator, the worst performance is 28.6%, 100%, 21.4% and 10.7% correspondingly. For the grey RPN with an equal weight of the risk factor, the elevator, escalator, baggage handling equipment and air-conditioner, relative to the worst-performing travellator are 118.1%, 100%, 122.2% and 133.3%, respectively. For the grey RPN with an unequal weight of the risk factor, the elevator, escalator, baggage handling equipment and air-conditioner, relative to the worst-performing travellator, the performance travellator, the performance are 114.8%, 100%, 119.7% and 133.4%, respectively.

3.6 Benchmarking with an escalator as the base performance equipment

To evaluate the performance of the equipment broadly, the performance obtained for each of the pieces of equipment was compared with the escalator. The following results were obtained. For the RPN approach, the relative performance of the elevator, baggage handling equipment, travellator and air-conditioner in their best performance is 112.5%, 20.8%, 100% and 43.2%, respectively. For the grey RPN with equal weight for the risk factors, concerning elevator, baggage handling equipment, travellator and air-conditioner in their best performance, the results are 97.1%, 124.2%,100% and 122.7%, respectively. For the grey RPN with unequal weights of risk factors, elevator, baggage handling equipment, travellator and air-conditioner, relative to the best performing escalator, the performance and 96.5%, 122.3%, 100% and 123.5%, respectively.

Concerning the worst performance, for the RPN approach, concerning the elevator, baggage handling equipment, travellator and air-conditioner, relative to the escalator, the worst performance is 28.6%, 21.4%, 100% and 10:7%, respectively. For the grey RPN with equal weights of the risk factors, the elevator, baggage handling equipment, travellator and air-conditioner, relative to escalator with the worst performance, the relative performance of the mentioned equipment are 118.1%, 122.2%, 100% and 133.3%, respectively. For the grey RPN with an unequal weight of risk factor, concerning elevator, baggage handling equipment, travellator and air-conditioner, in association with the escalator of the worst performance, the performance is 114.8%, 119.7%, 100% and 133.4% respectively.

3.7 Benchmarking with baggage handling equipment as the base performance measuring equipment

An attempt to appraise the performance of the equipment from a wide perspective leads the investigator to consider each other piece of equipment with the baggage handling equipment. The following results are obtained. For the RPN approach, the comparative performance of the elevator, escalator, travellator and air conditioner in their best performance is 540%, 480%, 490% and 208.4%, respectively. For the grey RPN with equal weight for the risk factors; regarding elevator, escalator, travelator and air conditioner in their best performance, the results are 78.2%, 80.5%, 80.5% and 98.8%, respectively. For the grey RPN with unequal weights of risk factors, elevator, escalator, travellator and air-conditioner, relative to the baggage handling equipment, the best performance is 78.9%, 81.8%, 81.8% and 100.9%, receptively. Concerning the worst performance, considering the RPN technique and taking note of the elevator, escalator, travellator and the air-conditioner, relative to the baggage handling equipment, the worst performance is 133.3%, 466.7%, 466.7% and 50%, respectively. By attempting to evaluate using the second technique, which is the grey RPN with an equal weight of the risk factors, the elevator, escalator, travellator and air-conditioner, relative to the baggage handling equipment whose worst performance is evaluated, the comparative performance of the defined equipment are 96.7%, 81.8% 81.8% and 109.1%, respectively. For the grey RPN with unequal weights of the risk factors, the elevator, escalator, travellator and air conditioner, relation to escalator with the worst performance, the relative performance of the mentioned equipment are 95.9%,83.5%, 83.5% and 11.4%, respectively. Benchmarking with the air conditioner as the base performance measuring equipment to evaluate the performance of a set of ground equipment that is key to the airport, a wide range of perspective is adopted. This idea leads to an enquiry of the performance of each piece of equipment against the air-conditioner.

The following results were obtained from the analysis first, the RPN method is considered in which the best performance of the air-conditioner is compared with the best performance of each of the following equipment: elevator, escalator, travellator and baggage handling equipment. The performance set is 260.4%, 231.4%, 231.4% and 48.2%, respectively. For the grey RPN method where the weights of risk factors are equal, the best performance of the air-conditioner is compared with the best performance of each of the following equipment: elevator, escalator, travellator and baggage handling equipment. The performance set is 78.2%, 81%, 81% and 99.1%, respectively. Considering the worst performance, the first method, RPN, is analyzed on the equipment. The worst performance of the air-conditioner is compared with the worst performance of each of the following equipment; elevator, escalator, travellator and baggage handling equipment, the performance is 88.6%, 75%, 75% and 91.7%, respectively. For the third method, grey RPN with an unequal weight of the risk factors, when the worst performance of the air-conditioner is matched against each of the following: elevator, escalator, travellator and baggage handling equipment, the performance is 86%, 75%, 75% and 89.7%, respectively.

3.8 Optimal failure computation using polynomial

To determine the optimal failure for each of the piece of equipment, the determining matrix, Fop, is first established. This as a three-by-three matrix that was created based on the top three best values of the performance evaluation given in Tables 1 to 5. To illustrate this choice, consider the first equipment, elevator. Information from the columns representing the RPN, grey-RPN_E and grey-RPN_D are extracted concerning the values attached to the ranks in each of the following columns. For RPN, the first three values are 729, 56 and 42. This is the first column of the optional failure matrix created. Consider the first three positions in grey-RPN_E, we have 0.333, 0.588 and 0.622, respectively. This represents the second column of the optimal failure matrix. The third column is obtained as 0.333, 0.506 and 0.587, respectively, by tracing the best three values under the grey-RPN_D column. To obtain the optimal failure value, the difference between the F_{op} and I is obtained, where I is the identity matrix. Thus, for the elevator, the following solution is true (Equation (11)):

$$\begin{bmatrix} 729 & 0.333 & 0.333 \\ 56 & 0.588 & 0.506 \\ 42 & 0.622 & 0.587 \end{bmatrix} - \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{bmatrix} = \begin{bmatrix} 729-\lambda & 0.333 & 0.333 \\ 56 & 0.588-\lambda & 0.506 \\ 42 & 0.622 & 0.587-\lambda \end{bmatrix} = 0 \quad (11)$$

By carrying out the analysis, the final equation is obtained as (Equation (12)):

$$-\lambda^3 + 729\lambda^2 - 850.768\lambda + 21.376 = 0 \quad (12)$$

The solution to $\lambda = 0.03$, 1.14 and 727.83

The same approach is used for other pieces of equipment. Thus, for the travellator, the following solution is true (Equation (13)):

$$\begin{bmatrix} 648 & 0.343 & 0.345 \\ 576 & 0.354 & 0.358 \\ 512 & 0.364 & 0.364 \end{bmatrix} - \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{bmatrix} = \begin{bmatrix} 648-\lambda & 0.343 & 0.345 \\ 576 & 0.354-\lambda & 0.358 \\ 512 & 0.364 & 0.364-\lambda \end{bmatrix} = 0 \qquad (13)$$

By carrying out the analysis, the final equation is obtained as (Equation (14)):

$$-\lambda^3 + 648.718\lambda^2 - 465.523\lambda + 167.832 = 0 \qquad (14)$$

The solution to $\lambda = 648$

3.9 Novelty the article

The key thrust of this article is to evaluate failures of selected airport ground equipment, which includes the elevator, escalator, travellator, baggage handling equipment and the air-conditional. These pieces of equipment are critical in the definition of customer service quality to passengers awaiting flights in airports or those on arrival from a flight. Although the literature has expressed concern on flight quality and customer service of passengers in airports, a major part of the literature focuses on the ride quality of passengers after securing a place in the aircraft. Extremely little attention was paid to passengers' comfort while awaiting flights, in moving to have a seat in the plane or arriving from a flight, which requires some rest periods before leaving the airport. In all these situations, both the luggage of the passengers and the passenger requires comfort. These are in luggage flow and the cooling comfort while awaiting the next action at the terminal hall. A new approach is presented to evaluate the failure of the equipment using the failure modes effects and criticality analysis and the grey relational analysis. Three novel methods were proposed for the first time, in the perspective of failure modelling of airports ground equipment. These are the RPN method, the grey RPN with equal weights of risk factors and the grey RPN with different weights of risk factors. The best and worst performances of each of the selected equipment were measured. Benchmarking of all other equipment relative to each of the selected equipment was done along with the directions of the best and worst performance. The final ranks were made after considering all equipment in each particular class.

Furthermore, while it is acknowledged that several researchers have involved can customer satisfaction models in airports, details on failure concerning the key equipment's and particularly the minimum possible failure control threshold of the key equipment such as elevators, escalators, baggage handling equipment and air conditioners have not been tracked. But knowledge of the least possible failure could help the maintenance manager to deploy manpower and resources to control such failures. A novel feature of the current work is the introduction of a polynomial for calculating the least possible failure for any ground equipment based on a matrix generated from the best performance values on each piece of equipment whose number is equivalent to the number of methods considered in the evaluation of the performance of the equipment. The RPN, grey-RPN_E, grey-RPN_D is correspondingly mapped to the best, next best and the third-best entries from the failure evaluated to form the matrix, whose results are transformed to a polynomial.

3.10 Uncertainty measurement

To establish the reliability of the findings, random uncertainty analysis was conducted on the RPN values for all the equipment analyzed. Random uncertainty, the ratio of the difference between the maximum value and the minimum value of the RPN to the number of values considered under each equipment, was observed. Moreover, percentage uncertainty, which is the product of absolute uncertainty and 100 units divided by the measurement, was considered for the analysis. The summary of the results is given in Table 6.

Table 6. Absolute and percentage uncertainty for the RPN values of all equipment.

Equipment	Absolute Uncertainty	% Uncertainty
Elevator	98.90 ± 72.10	72.90
Travelator	202.00 ± 56.36	27.90
Escalator	202.45 ± 56.36	27.84
Baggage handling equipment	53.35 ± 9.27	14. 38
Package air conditioner	78.83 ± 23.08	29. 28

Table 6 reveals the highest and lowest % uncertainty with the elevator and the baggage handling equipment, respectively. These are 72.90 and 17.38, respectively. The high value of 72.90 as a percentage uncertainty does not mean low data reliability but high variability in the opinion of the expert who conducted the assessment. This is understandable as the expert opinion differentiates the elevator as the most critical equipment in the system that needs the greatest attention. Also, the baggage handling equipment is observed to be the one that requires the least attention in service.

3.11 Limitations, practical uses of the findings and contributions

The conducted equipment failure assessment has certain limitations resulting from the challenges with complex interactions. The FMEA-GRA method hardly considers the multi-failure situations and the complexity of the ground handling equipment. This weakness can be corrected in the future by considering the infusion of the Markov chain methodology into the proposed framework to mitigate interaction capability deficiencies. Moreover, there is another limitation of the FMEA-GRA method termed the static analysis. This refers to the consideration of the method on a one–time basis and fails to consider real-time changes. Interestingly, the Markov chains mentioned earlier could serve this second purpose of analyzing when the period of analysis changes. Also, the FMEA-GRA method is historical data-dependent, which may not work well for a new airport whose ground service handling equipment is being planned. To overcome this limitation, data could be imported from an existing airport base to the new one, complemented with simulation data.

In this paper, the FMEA-GRA method has been applied to an airport with findings which appear to have practical use from various dimensions. First, the grey relational analysis aspect of the combined FMEA-GRA method has the potential to support sound decisions where limited maintenance data and poor maintenance information are available. Thus, in the joint FMEA – GRA method, the maintenance manager can improve decision-making where uncertainty prevails, leading to more assured results from risk assessments. Secondly, understanding and establishing potential failure modes in baggage handling equipment reveals how to eliminate non-value adding activities with significant downtime reduction. Therefore, there is an improvement in ground service operational efficiency through this route. Third, maintenance schedules could be updated and improved using the findings of the FMEA-GRA method's application to airport ground services. Since this helps the plant to transform reactive to proactive maintenance, the optimization of maintenance strategies is aided by the results obtainable from the application.

Moreover, the application of the FMEA-GRA method to airport ground services delivers results that align with the broader reliability engineering practices. It achieves this through the provision of a data-oriented method, which priorities risks within a complex airport working environment. The combined FMEA-GRA method offers results that provide actionable improvements to reliability. Furthermore, the integrated FMEA-GRA method offers substantial theoretical advancements, changing the assessment platform from a subjective, multiplication-oriented perspective to a mathematically rigorous, objective decision structure. It contributes the following benefits to the literature: First, the proposed method permits managing uncertainty, promoting more objective results. Second, the ambiguity concerning the RPN is resolved as the grey relational analysis focuses on distance measurement instead of just multiplication alone.

3.12 Maintenance recommendations

Arising from the application of the FMEA-GRA method for the ground services in the airport, the following actionable maintenance recommendations are provided:

1. High-risk equipment components should be prioritized: The results obtained from the FMEA-GRA methodical application show that the following components have the highest risk priority numbers in each piece of equipment: controller (elevator), controller (travelator), drive system (escalator), controller (baggage handling equipment), and power aircraft board (package air conditioners). These are highly crucial components that require urgent maintenance intervention. The principal intervention that could be done to controllers in elevators, travelators and baggage handling equipment typically includes the following. First, a smart sensor upgrade could be pursued to aid improved load sensing, door operation and accurate smoothing. Moreover, introducing the variable frequency drives as upgrades of

older drives prevents excessive energy consumption and reduces noise since torque and motor speeds are adjusted dynamically. Furthermore, regeneration drives could be introduced that aid in the recycling of excessive energy produced as the elevator descends. This promotes a reduction of energy costs.

2. Establish spare parts strategy: With the established failure modes, the maintenance of high-risk spare parts should be available on request during corrective maintenance sessions. This will eventually lower downtime significantly. Critical spare parts for controllers in elevators that should be stocked include inverter drives, relays and contractors. For power circuit boards in package air conditioners, power transistors, relays, capacitors and fuses could be stocked.

The maintenance recommendations suggested earlier have the potential to improve ground service efficiency in airports if addressed.

4 Conclusions

In this paper, a novel approach to establishing the failures of key ground equipment, which involves elevator, escalator, travellator, baggage handling equipment and the air conditioner was discussed and implemented in an airport operating in a developing country. Three methods namely the RPN, grey RPN_E and grey RPN_D were developed and the failures of equipment determined based on the failure modes effects and atonality analysis and the grey relational analysis. The conclusions based on the study are as follows:

1. The three models, the RPN, grey-RPN_E and grey-RPN_D are effective methods in determining the failures of the ground equipment in an airport.
2. The eigenvalue method by which polynomial equations are developed and solved is a component approach to establishing the failure of the ground equipment of the airport.
3. The best values for the equipment performance through the three methods of RPN, grey- RPN_E and grey- RPN_D are respectively as follows: (729,0.333 and 0.333) for elevation, (648,0.343 and 0.345) for travellator, (648,0.343 and 0.345) for the escalator, (135, 0.426 and 0.422) for baggage handling equipment, and (280, 0.421 and 0.426) for air conditioning.

In the future contributions in the area of optimization of the process using the Taguchi method, genetic algorithm and combined Taguchi and genetic method may profit from the work.

4.1 Appendix

Table 7. Risk ranking for all equipment

Component Name	Occurrence (O)	Severity (S)	Detectability (D)	RPN = O x S x D
Elevator				
Elevator Car	1	8	2	16
Machine Drive	1	8	1	8
Brake System	1	8	1	8
Landing Door	8	7	1	56
Counterweight Tension Pulley	3	7	2	42
Car Buffer	3	7	2	42
Over-speed Governor	2	8	2	32
Controller	9	9	9	729
Counterweight Frame	2	7	2	28
Car Guide Rail	2	7	2	28
Travelator				
Handrail	1	6	8	48
Landing Plate	7	8	2	112
Braking System	2		2	28
Truss	1	7	8	56
Drive System	8	8	8	512
Controller	9	8	9	648
Lubrication System	2	7	2	28
Tracks	3	8	3	72
Balustrade Panels	3	5	2	30
Comb Plates	2	7	8	112
Safety Devices	8	8	9	576
Escalator				
Landing Platform	8	8	2	128
Truss	1	8	8	64
Tracks	3	8	2	48
Steps	2	7	9	126
Handrail	1	6	8	48
Escalator Exterior	3	5	2	30
Drive System	8	8	8	512
Lubrication System	2	7	2	28
Braking System	2	7	2	28
Safety Devices	9	7	9	567
Controller	9	8	9	648

Table 8. Risk ranking for all equipment

Component Name	Occurrence (O)	Severity (S)	Detectability (D)	RPN = O x S x D
Baggage Handling Equipment				
Belt	3	8	1	24
Truss	1	7	2	14
Controller	5	9	6	135
Drive System	2	8	3	48
Drum Roller	2	7	3	42
Bumper	6	1	1	6
Carrier	3	6	2	36
Chain	3	9	2	54
Slat	6	2	2	24
Lubrication System	6	8	2	96
Motor/Gear	6	9	2	108
Package Airconditioner				
Compressor	2	9	6	108
Condensing Fan	2	7	5	70
Evaporator Fan/Blower	1	8	5	40
Condenser Coil	1	8	5	40
Evaporator Coil	1	8	5	40
Refrigerant	4	6	5	120
Air Filter	1	3	1	3
Electrical Control System	3	8	6	144
Power Circuit Board	5	8	7	280
Piping System	1	7	4	28
Expansion Valve	1	8	6	48
Thermostat	1	5	5	25

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