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INNOVATIVE AIRPORT 4.0 CONDITION-BASED MAINTENANCE SYSTEM FOR BAGGAGE HANDLING DCV SYSTEMS

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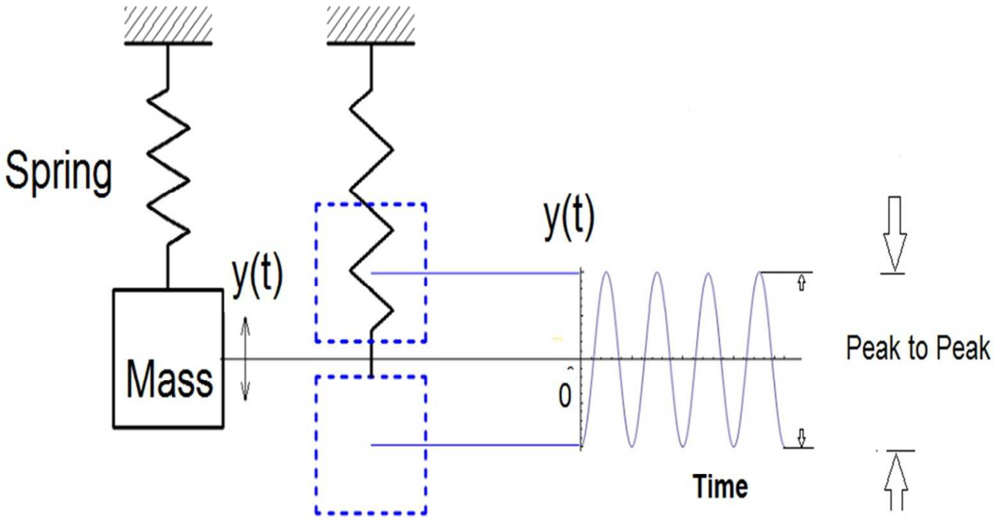

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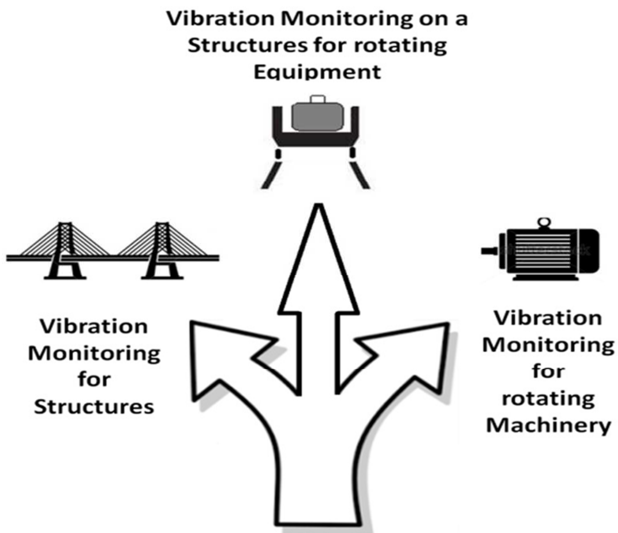

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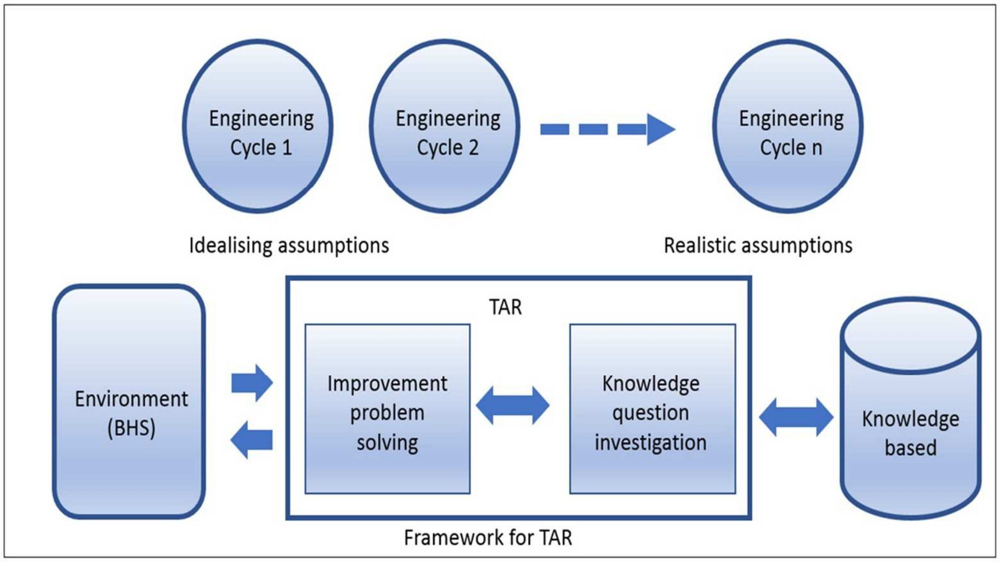

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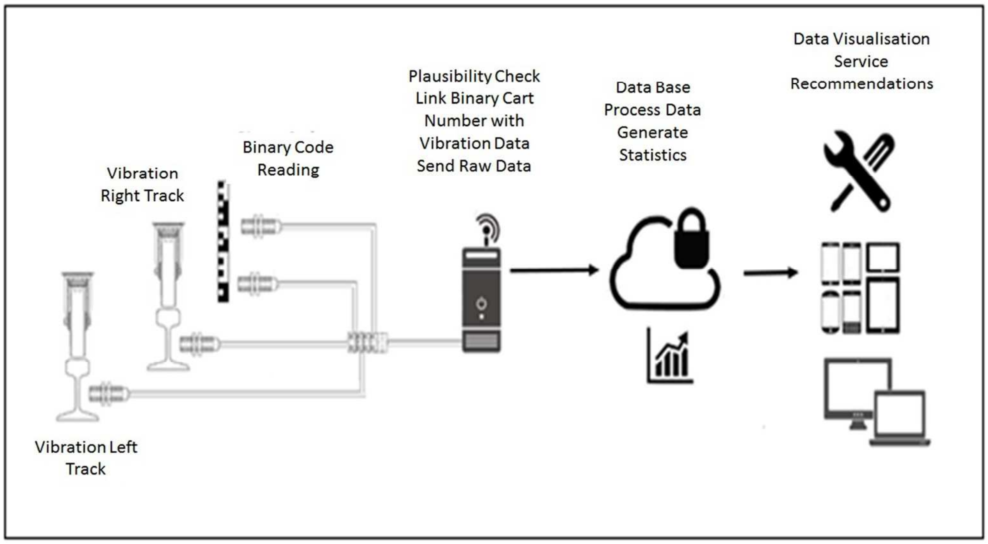

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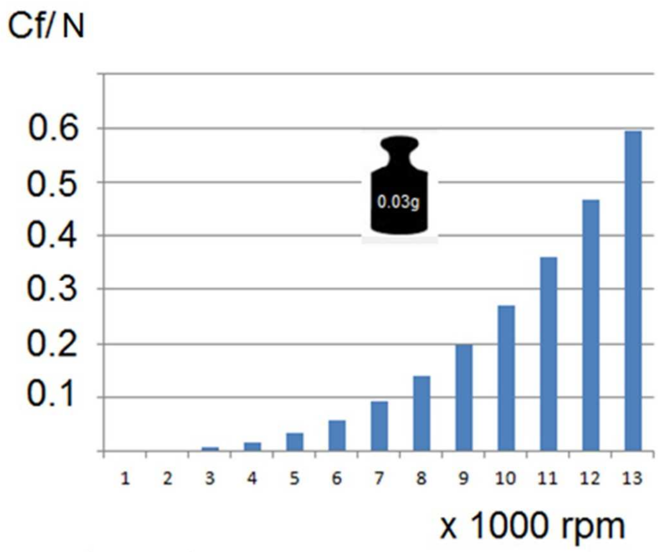

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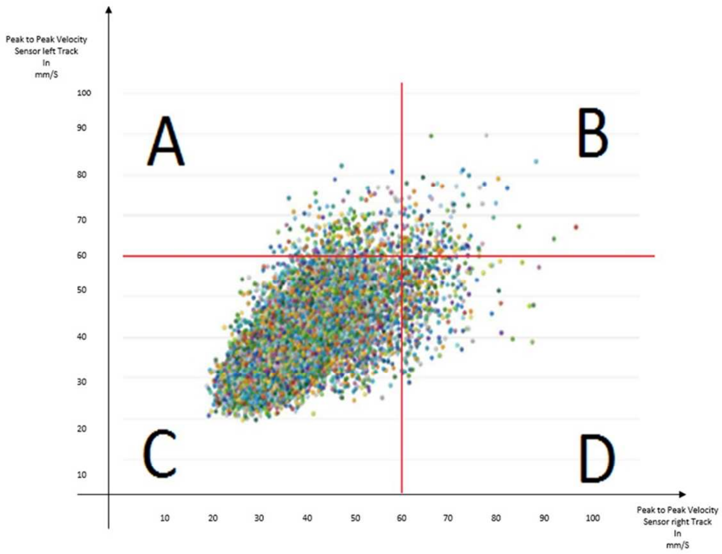

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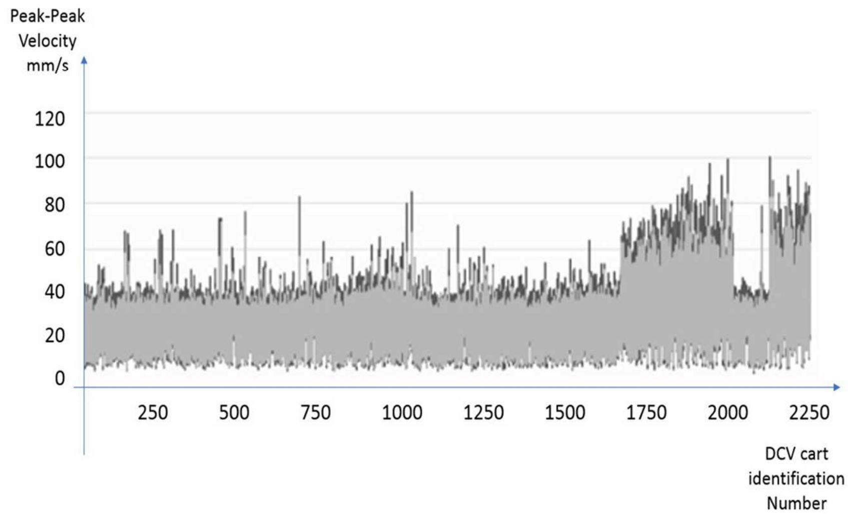

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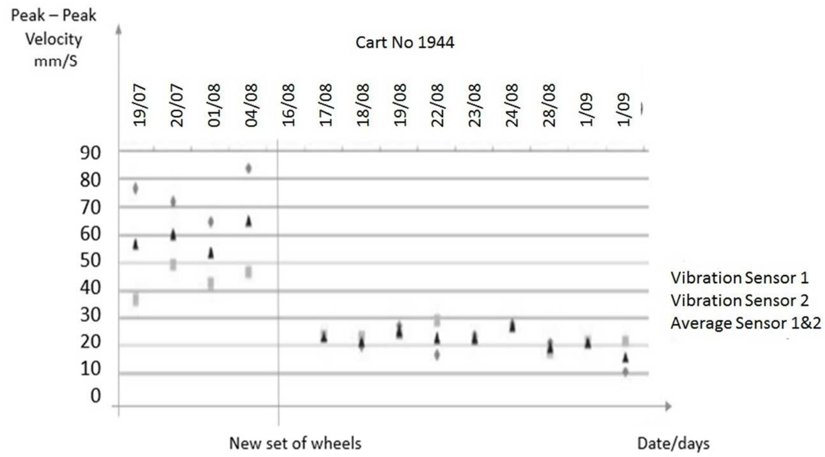

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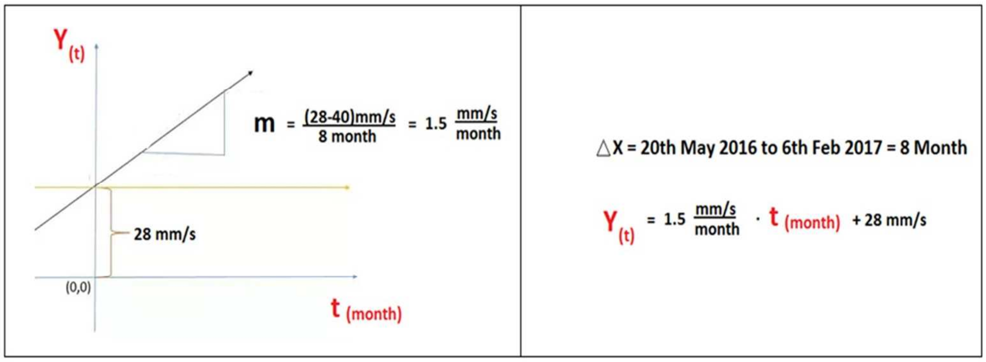

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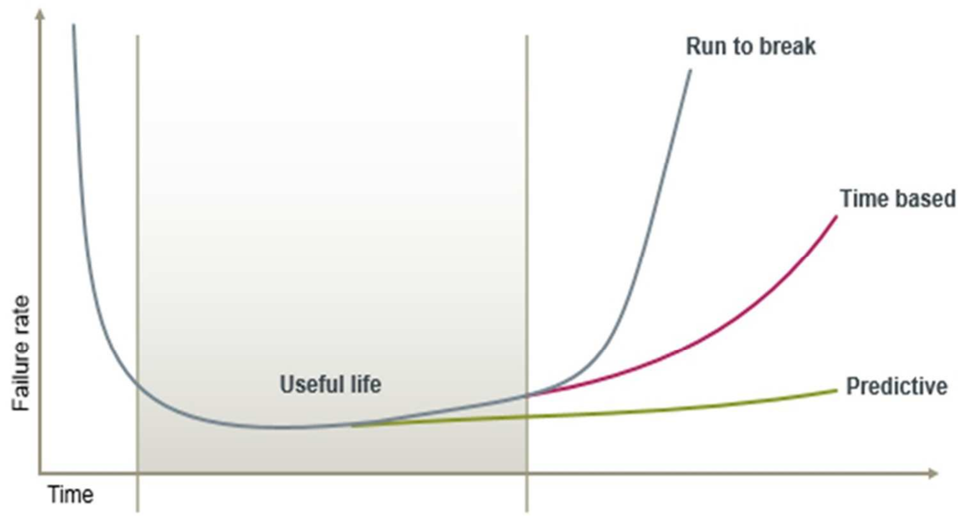

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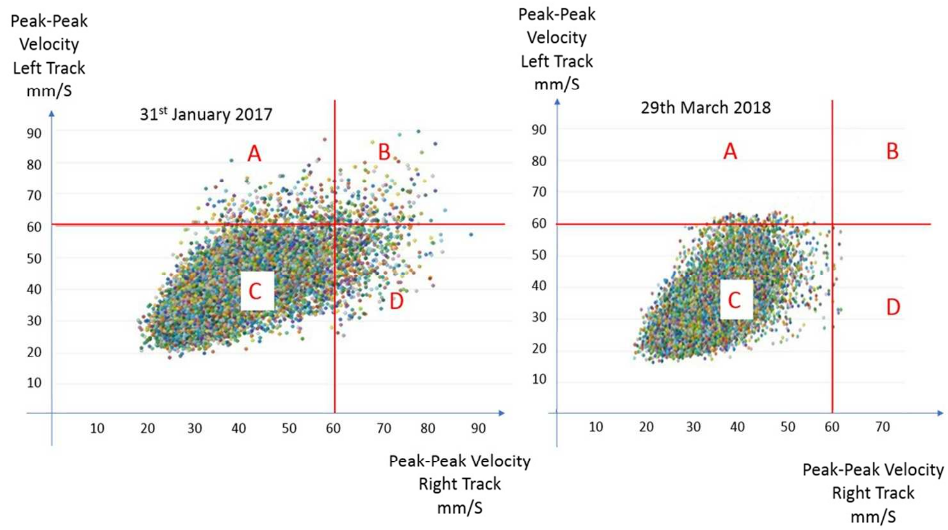

figure 12

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$$Cf = m \, x \left(\frac{rpm}{1000}\right)^2$$

m (Mass)

rpm (Rotation per Minute)

341x190mm (96 x 96 DPI)

Innovative Airport 4.0 Condition-Based Maintenance System for High Speed Baggage Handling Direct Coded Vehicle Systems at Airports

Abstract

Purpose:
This study investigates the problem of failure in Heathrow airport's baggage handling system.

Design:
In cooperation with Siemens Airport Logistics and Siemens DF (digital factory) and their open, cloud-based IoT (Internet of Things) operating system (MindSphere), an innovative condition-based maintenance system was developed to meet the requirements of 21st century airport systems and Industry 4.0.

Methodology:
An empirical experimental approach was used to install a vibration condition monitoring pilot test for the high-speed destination-coded vehicle (DCV) system that transfers baggage between terminals. The objectives were first to find a solution to the airport's operational issue, and also to test Siemens' Mindsphere platform. Vibration data collected from track sensors as the carts passed by at high speed was streamed securely to the Mindsphere platform.

Findings:
A dashboard was created which showed a clear trend of increasing vibration velocity with age and use of baggage cart wheels, caused by wheel mass unbalanced inertia. Vibration monitoring has been used to measure movement in static structures and rotating machinery, but its application here represents the first time it has been applied on a stationary structure carrying high-speed rotating machinery. The analysis identified issues with the process of DCV cart wheel maintenance at the airport which were quickly resolved.

Practical Implications:
The DCV cart maintenance programme has since been re-architected from a time-based maintenance approach to being based on the actual condition of the wheels of each cart, applying Industry 4.0 techniques that are now being investigated for several major airports worldwide.

Keywords: *Baggage handling system maintenance, Condition Monitoring, Time-based Maintenance, Siemens Mindsphere, destination-coded vehicle systems, Airport 4.0, Industry 4.0, Service 4.0*

1 Introduction

Industry 4.0 thinking and the industrial Internet of Things are revolutionising industrial operations through better visibility, connectivity, and improving predictive maintenance capabilities of organisation, resulting in improved reliability and delivery of services. Smart systems and Internet-based solutions that characterise Industry 4.0 greatly impact and change manufacturing processes and practices, maintenance strategies and maintenance management (Li *et al*., 2016). Companies that successfully use Industry 4.0 optimise the system performance by integrating people, processes, and equipment using sensors and smart devices (Liu *et al*., 2012; Schmidt *et al*., 2015). The smart devices enable integration between operators and machines, thereby improving operators' predictive decision-making capabilities through access to real-time information. This facilitates better collaboration, faster problem-solving and improved innovation at all levels in the organisation. Equipment and devices become intelligent assets capable of reporting a wealth of operation information including diagnostics leading to faster and better business decisions that can help increase productivity, improve quality and targets cost-efficiency (Kolberg and Zühlke, 2015).

The last three years have delivered a plethora of literature on the application of Industry 4.0 to manufacturing processes but little evidence on the application to predictive maintenance activities of an organisation (Li *et al*., 2016). The lack of research creates operational dilemmas for many organisations as to how best to optimise their maintenance strategies and processes to enable a transition towards Industry 4.0. There are also concerns that starting too early may result in fatal errors for the company due to lack of available resources and information on successful application of Industry 4.0 for predictive maintenance (Schmidt *et al*., 2015; Wang *et al*., 2015).

Research into the application of predictive maintenance capabilities for transforming airport baggage handling systems to be ready for Industry 4.0 transition is even less evident. Industry 4.0 for airport baggage handling systems poses several specific challenges. The complex handling systems often contain thousands of different assets, with failure of just one component causing the whole system to go out of service, or to only work at reduced capacity. The common maintenance practice for baggage handling systems is 'time-based', but this is often not adhered to and drifts into 'run-to-break' maintenance with unplanned system downtime, causing high failure costs and inconvenience to thousands of passengers. ..

The focus of this paper is on one of the pillars of operational excellence - 'continuous maintenance improvement'. Through the application of condition monitoring techniques, predictive maintenance capabilities of baggage handling systems can be improved, hence increasing critical equipment availability and reliability. It is the aim of every airport to reduce the incidence of baggage handling failures as far as possible. Practically, this means that during operational period, the system is kept 'alive' and time-based maintenance is performed during non-operational hours. The problem nowadays is that time-based, or 'preventative maintenance' programmes can easily default to corrective maintenance activities, known as run-to-failure (RTF) or reactive maintenance (Wang *et al*., 2015). Maintenance tasks become scheduled without the occurrence of any monitoring activities or overlooking conditions of the equipment in real-time (Li *et al*., 2016). This often results in failed baggage handling equipment that has to be repaired or replaced during operational periods (Ni and Jin, 2012). With many baggage handling systems working at near full capacity, such breakdowns will delay customers bags reaching the outgoing aircraft in time, hence leading to high costs for liquidated damages for late bags to be paid to airlines. Furthermore, additional costs for maintenance, repair or replacement are incurred due to sudden failures (Haider, 2013).

Heathrow studied in this research operated a destination-coded vehicle (DCV) baggage cart system that went into operation in 2008. As with many other large airports, baggage is transported at high speed in carts on rails to cover the long distances between airport terminals. The design is similar to that of a rollercoaster, with individual carts on wheels running on tracks. Each cart is boosted along by a succession of magnetic linear motors positioned at various locations beneath the tracks (Heinz and Pitfield, 2011).. When the existing system was relatively new and stable, Operations and Maintenance (O&M) professionals adhered to manufacturer recommendations and maintained the baggage handling systems on a regular time based schedule. After extensive use, system downtime incidents increased and now the efficacy of the maintenance strategy for the DCV system is questioned.

Increases in unplanned system downtime at airports have caused Senior Management to consider a strategic change for selected critical elements in their baggage handling systems. The technique of condition-based maintenance (CBM) is well known in the industry, however until recently, micro-processor speeds were not fast enough for it to be developed. CBM solutions were custom engineered but reputed as ‘too expensive’. Modern multicore processor techniques, however, make complex CBM solutions possible and cheaper to realise although there is no evidence that CBM technology has yet been fully implemented in any baggage handling system anywhere in the world. This paper will illustrate the application of key features of Industry 4.0 including developments related to cyber-physical system (CPS), Internet of Things (IoT), and big data processing, to improve the reliability of the DCV system though CBM.

This leads us to address two research questions in this study:

Can condition based monitoring (CBM) be implemented into a baggage handling system whilst in operation?

Is condition-based maintenance appropriate for time-critical maintenance strategies that support Industry 4.0?

This paper therefore considers the problem in detail, drawing on the existing literature. It then discusses a research design and pilot study to test the concept and presents the results of the pilot.

1.1 Background Research

Maintenance is a logistical and organisational function for integration into production processes. Its performance efficiency and effectiveness are difficult to measure in absolute terms, so this has to be defined and measured in relative terms of economic, technical or organisational ratios (Muchiri *et al*., 2011).

Previously, operating ratios were considered adequate indicators of maintenance performance. In this context, most commonly used ratios included maintenance cost ratio to plant area, maintenance cost ratio to quantity of directly employed people, and maintenance cost ratio to the number of units produced (Garg and Deshmukh, 2006; McKone *et al*., 1999). These ratios had limitations due to being dependent on each specific plant for which they were developed. Specific characteristics for each industry have been identified in the literature as constraints to the development of maintenance management systems. These include: information systems support (Oelsner, 1979), the extent of centralisation of the maintenance departments and technical complexity (Swanson, 2001).

It is difficult to compare ratios of different plants and different organisations. Meaningful comparisons of maintenance performance efficiency between them cannot be done without standards (Parida, 2008). However, new innovative approaches tend to emphasise a more balanced view of maintenance performance measures, namely, equipment-related performance, task-related performance, cost-related performance, immediate customer impact related performance, and learning and growth related performance (Kutucuoglu *et al*., 2001). Quality and Lean/Continuous Improvement programs, modern information technology and the evolution of performance measurement systems, have helped to promote the proliferation of maintenance performance measures and measurement (Bamber *et al*., 2004; Kolberg and Zühlke, 2015) (Liu *et al*., 2007). However, it is important to note that there are different forms of maintenance and some may be more appropriate than others.

In this paper, we explore the differences in maintenance strategies and the development of a new technique for establishing effective, efficient and cost-effective maintenance for DCV baggage handling systems.

1.2 Preventative Maintenance and Time-based Scheduled Maintenance

Preventive maintenance (PM), also known as time-based maintenance (TBM) was introduced in the 1950s and a common definition in the literature is: *"The care and servicing by personnel for the purpose of maintaining equipment in satisfactory operating condition by providing for systematic inspection, detection and correction of incipient failures either before they occur or before they develop into major defects"* (Ahmad and Kamaruddin, 2012). The main aim of PM is to follow planned guidelines to avoid breakdown or malfunction. Its strategy relies on estimated probabilities that equipment will break down. This is known as 'mean time between failures' (MBTF). It is a measure of how reliable a hardware component is (Engelhardt and Bain, 1986). Typical PM work includes inspection for wear, cleaning, lubrication, parts replacement and re-adjustment, done routinely to prevent breakdown. PM comprises of planned, or scheduled, maintenance done after specific periods of time and machine usage (Duffuaa and Ben-Daya, 2009; Li *et al*., 2016). 'Preventive Maintenance' has been adopted by some airports as a first countermeasure to reduce the likelihood of breakdowns (Holloway and Nwaoha, 2012) Campbell and Reyes-Picknell, 2016).

1.3 Total Productive Maintenance

TPM is a Japanese concept, based on Productive Maintenance methodologies. It was first introduced in Japan in 1971 by Nippon Denso Co. Ltd, a supplier of Toyota Motor Company (Ahmed *et al*., 2005). TPM is an innovative approach to maintenance that optimises equipment effectiveness, eliminates breakdowns and promotes autonomous maintenance by operators through day-to-day activities involving total workforce (Kaur *et al*., 2012; Venkatesh, 2007).

TPM brings maintenance into focus as a necessary and vitally important part of a manufacturing business. Its powerful structured approach assists change in the mind-set of employees, and an organisation's entire work culture. It seeks to engage all levels and functions to maximise overall effectiveness of production equipment. It enhances existing processes and equipment by reducing mistakes and accidents and is a world class manufacturing (WCM) initiative (Dogra *et al*., 2011). Whereas maintenance departments are the traditional centre of preventive maintenance programs, TPM seeks to involve workers from all other departments and levels, including the plant-floor to senior executives, to ensure effective equipment operation.

1.4 Predictive and Condition-based Maintenance

Predictive Maintenance (PdM) is also known as condition-based maintenance (CBM). It is designed to determine the condition of equipment whilst it is working. By observing working equipment, accurate, timely information can be acquired on its condition and performance enabling equally accurate knowledge and decisions to predict when maintenance should be scheduled (Li *et al.*, 2016; Mobley, 2002).

PdM therefore brings cost savings over TBM because its requirement is based on actuality, rather than estimates of condition and performance (Tickoo *et al.*, 2010; Wang *et al.*, 2015) and, PdM requires less spare parts to manage. In PdM, the diagnostic techniques used to measure condition can include temperature, noise, vibration, lubrication monitoring. When indicators reach a predetermined deterioration level, maintenance is undertaken to bring the equipment back to the desired condition. This means that the equipment is only taken out of service when evidence exists that deterioration has occurred. PdM is based on the same principles as PM but involves a different standard for determining requirements for specific maintenance services. PdM's advantage emanates from the fact that maintenance is scheduled when needed (Hashemian and Bean, 2011).

A better way to avoid breakdowns is a maintenance strategy that monitors and report in real-time the condition of a machine or device in use, a key principle of Industry 4.0, so its remaining life can be estimated. This is called 'Condition Monitoring' and 'Diagnostic Engineering Management'. Researchers have noted considerable evidence that 'Condition Based Maintenance' gives economic advantages in most industries and is the best available strategy for preventing unexpected system downtime (Carden, 2004; Li *et al.*, 2016; Randall, 2010; Rao, 1996) (Garcia et al. 2006). The most common methods of 'Condition Monitoring' are infrared, lubricant or 'Vibration Based Condition Monitoring'. The following section focuses on Vibration Theory (Blake, 1988) and 'Vibration Condition Monitoring', which is the key feature of PdM applied in this paper.

1.5 Vibration Theory

The precise treatment of vibration can be associated with the basic law of elasticity described by Hooke in 1678, Newton's second law of motion (1687) and the principals of differential described by Leibnitz, also in 1687. A theoretical solution of the problem of vibration was found in 1713 by the English mathematician Brook Taylor (1685 – 1731), who also presented the famous Taylor theorem. A century later 'The Theory of Sound" was published by Lord Rayleigh and this still considered a classic (Shabana 1996). Vibration theory was known for centuries, however its analysis in industry began half a century ago with simple analytical methods (Holloway and Nwaoha, 2012). A common spring mass system illustration that can be found in literature is shown in Figure 1.

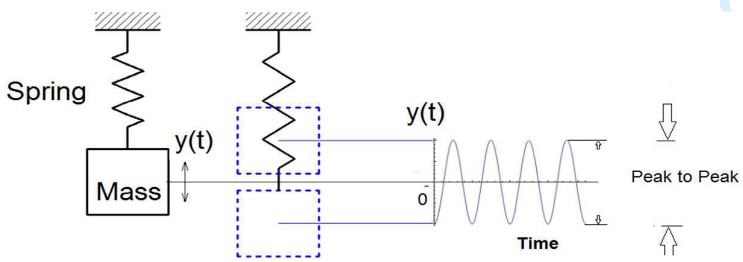

Figure 1 – Relation y(t) of a 'Spring-Mass' System

1.6 Vibration Condition Monitoring

The development of digital computers in the 1950's made it possible to engineer the first vibration analysis systems (Brandt, 2011). Many researchers speculated that fault detection caused by changes in response of systems, has been in practice since man first used tools. The basic idea persists today that commonly measured parameters are functions of the physical system for instance mass, damping or stiffness (Fritzen, 1986). Therefore, changes such as reductions in stiffness caused by bearing wear and cracks, or loosening of a connection will cause significant changes in the vibration spectrum. According to Gupta (1997), changes in vibration characteristics provide intuitive information about damage. However, there are many factors that make vibration-based condition monitoring difficult to implement in practice (Randall, 2010) and according to the literature, the majority of the projects were not successful (Carden and Fanning, 2004).

The reason for that were the non-availability of sufficient processor speed. With the availability of multi-core processor techniques in 2007 even more complex applications became feasible which opened a new area of condition monitoring. From perspective of PdM/CBM, access to cloud computing environments that are a key feature of Industry 4.0, create a collaborative community for processing and analysing industrial big data collated from remote machines, thereby facilitating maintenance activities in real-time based on actual condition of the machine (Li et al., 2012).

Recent studies show that methods of vibration monitoring have developed significantly, with rising performance of computers and with better sensor technology (Ebersbach and Peng, 2008; Harris and Barnsby, 2001) and many new methods have been established for dynamic data analysis of rotating machines (Combescure and Lazarus, 2008; Prashad, 2006). Detecting vibration behaviour in rotating machinery is the most practiced form of 'Vibration Based Condition Monitoring' to identify damage prior to a fatal breakdown (Randall, 2011). However, more complex CBM applications to monitor static structures are usually custom designed as standard software solutions are less readily available (Alvandi and Cremona, 2006). The disadvantage for such custom-engineered and developed solutions is high cost. For most industrial processes, such solutions are too expensive, so for decades, only NASA, aviation and oil rig industries investigated the more complex condition base monitoring solutions to their problems. Thus, there are two well developed vibration monitoring methods, shown in Figure 2.

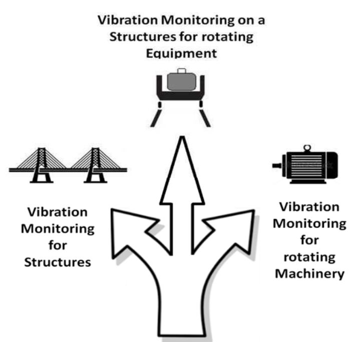

Figure 2– Vibration monitoring for condition-based maintenance

The left path indicates structural vibration measurement, whilst the right path shows vibration monitoring for rotating machines (Tondon and Choudhury, 1999). A new central path would use techniques from structural and rotating vibration monitoring methods.

Measuring vibration generated by a wheel and transmitted to a track so that the wheel condition can be monitored is new. There is however a technique available used for the rail industry, but sensors are installed on the train, the moving part. In DCV systems, usually such systems have several thousand carts so the technique of having sensors on board would be of high cost and not affordable. DCV carts are powered by linear motors on modular conveyor elements. They have no power source on board so installing a measuring system would be difficult and expensive.

For these reasons, the author designed a system that measures wheel wear via the vibration transmitted from the DCV cart to the track.

Vibration condition monitoring performed on structures and rotation machines is well described in the literature. There is no literature where the condition of a DCV caster wheel (rotating element) was measured using vibration on a structure (track).

2 Methodology

Technical Action Research (TAR) methodology was selected as 'an approach in which the action researcher and stakeholders collaborate in analysis of the problem and in development of a solution based on the diagnosis.' (Wieringa, 2014) It was selected because it is known as a strong method to assist rapid problem-solving.

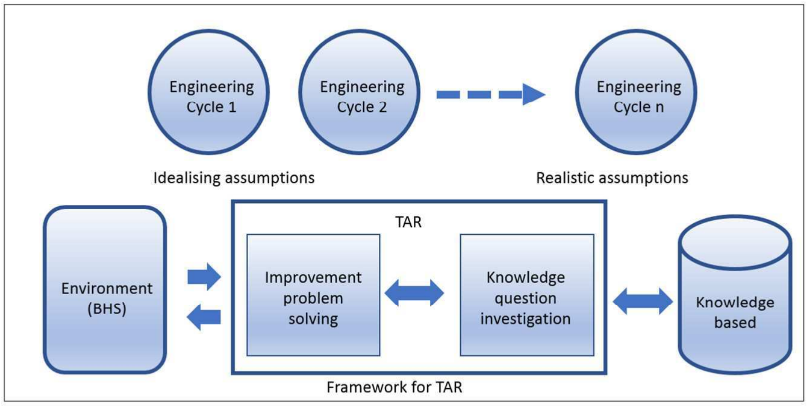

Figure 3 – The technical action research cycle (Trist, 1980)

The author negotiated a role as a facilitator between Heathrow as the practitioner and Siemens as the technical solution provider. Airport baggage handling system are huge technical systems and Socio-Technical Systems theory was used (Thakker *et al*., 2011) . The research has a high level of practical relevance and can be used with quantitative and qualitative data, enabling in-depth knowledge about baggage handling assets, their technology and potential issues.

2.1 The Pilot Project in Heathrow's DCV system

The author has been given permission by Heathrow Airport Limited to develop this Condition Monitoring system to monitor the caster wheel condition of 2200 destination-coded vehicles (DCV) system in the north tunnel of Terminal 5.

The tunnel has high speed conveyors that are operational for 18 hours per day and capable of running 12m/s with a second slow running line that runs at 2m/s.

Passing carts generated vibration that was transmitted to the tracks. Two accelerometers were also installed and connected to Siemens condition monitoring system (CMS) module to gather high frequency vibration data for CM analysis (Siemens AG, 2013). The vibration data gained using Siemens' CMS product have already been proven valid in various CM projects.

A pair of photo sensors were installed facing the passing carts; one to read a binary identity-code strip so the vibration sensor analysis can be matched to a specific cart; another to read seventeen alternating bits used to trigger the binary code reading of the code strip. The sensors were connected to the server via an input module (Figure 4).

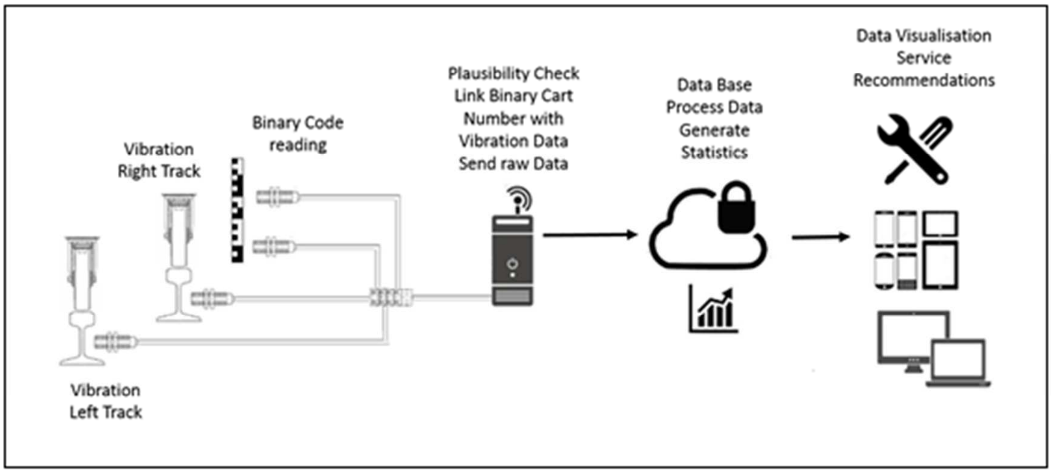

Figure 4 – Diagrammatic representation of the pilot study.

Data was collected over a period of 6 months and 3.5 million vibration measurements were analysed to determine threshold vibration peak-to-peak velocity. The data was used to track the wear of wheels over time and to determine which wheels needed replacement. The results were compared with existing measures to demonstrate that vibration monitoring could be used as a predictive model for condition-based maintenance.

3 Findings

Airport use time-based maintenance to service DCV carts. Carts with wheels nearing their end of life failed, causing catastrophic collisions that blocked tunnels and caused excessive down time.

The research findings demonstrate a clear trend of increasing vibration velocity with age and use of the baggage cart wheels. The DCV carts ran smoothly on lines that operated slowly (0.5 to 2.5 m/s) but the behaviour at high speed was different. Some carts ran smoothly, others generated some noise and some generated loud oscillating thuds.

These observations raised questions as to why there were so many differences in noise generation and why the differences were so pronounced on high speed lines. The reason indicated from research in automobile industry suggested that centrifugal forces created by imbalance conditions increases by the square of the rotation speed of the wheel "rpm". If the speed of the cart is doubled, the force quadruples; if the speed is tripled the force increases by a factor of nine. An equation for estimating force is (Fricker, 1990):

$$Cf = m \times \left(\frac{rpm}{1000}\right)^2$$

m (Mass)
rpm (Rotation per Minute)

The following example is for that of automobile tyres, but it gave a good explanation of observations at the airport study. At 12 m/s, the speed in the tunnel line is over 8 m/s higher than on other lines in the system. As a consequence, the exponential contribution of the centrifugal force created by wheel imbalance causes the cart parts to fail. The force generated by such excessive vibration leads to dramatic shortening of the useful bearing life (Goodwin *et al*., 2003).

The example in Figure 5 is for a car tyre illustrating the imbalance caused by 0.03g in centrifugal force (Cf) at various speeds (Gough and Whitehall, 1962).

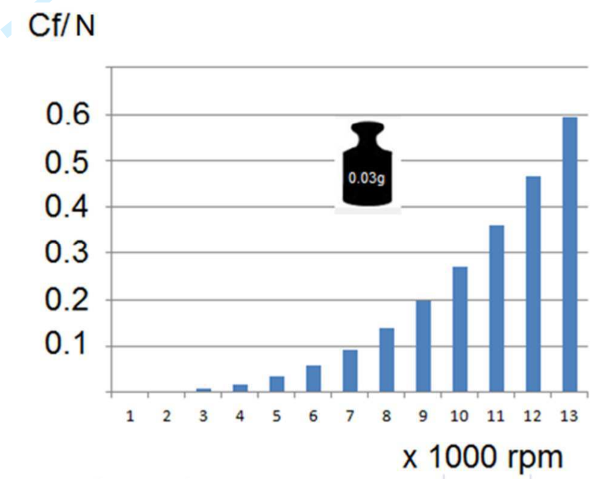

Figure 5 – Imbalance of car tyres at various speed

The exponential increase in centrifugal force due to the wheel mass unbalanced inertia along the high-speed section can be utilised, since the vibration transmitted to the tracks can be measured and its intensity varies greatly depending on the condition of wheels on the carts. Vibration data was collected from carts passing the sensor for over three weeks in the winter of 2016/2017 and this was plotted (Figure 6) and analysed. Analysis of the results indicates that, at about 60 mm/s, vibration cart wheels will be close to their end of life. The study enabled a hypothesis that carts producing vibration up to 60 mm/s (shown in cell C) are within useful life and carts with data over 60 mm/s (Cells A, B & D) are close to end of life