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- Encouraging research in the operation and maintenance, facilities management and asset management sectors, and proper management of properties. The magazine will conduct research, scientific reviews or technical studies on the following topics in these sectors:

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- Operations and Maintenace Standards
- Maintenance Performance Indicators
- Total cost of ownership
- Environment Management Systems
- Safety Management Systems
- Energy Management
- Health and safety polices
- KPI Methodologies And definition

Asset Health Index Method. A Case Study for Process Pumps Fleet.

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Abstract

An Asset Health Index (AHI) is a tool that processes data about asset's condition. That index is intended to explore if alterations can be generated in the health of the asset along its life cycle. These data can be obtained during the asset's operation, but they can also come from other information sources such as geographical information systems, supplier's reliability records, relevant external agent´s records, etc. The tool (AHI) provides an objective point of view in order to justify, for instance, the extension of an asset useful life, or in order to identify which assets from a fleet are candidates for an early replacement as a consequence of a premature aging.

Keywords: Assets management, capital investment, operation and maintenance decision making, life cycle analysis, assets health.

Introduction

An Asset Health Index (AHI) is an asset score, which is designed, in some way, to reflect or characterize the asset's condition and thus, its performance in terms of fulfilling the role established by the organization.

AHI represent a practical method to quantify the general health of a complex asset. Most of these as-sets are composed of multiple subsystems, and each subsystem can be characterized by multiple modes of degradation and failure. In some cases, it may be considered that an asset has reached the end of its useful life, when several subsystems have reached a state of deterioration that prevents the continuity of service required by the business.

Therefore, the health index, based on the results of operational observations, field inspections and laboratory tests, produces a single objective and quantitative indicator. It may be used as a tool to manage as-sets, to identify capital investment needs and maintenance programs, allowing:

Compare the health of equipment located in similar technical locations, to study possible premature deterioration and optimize operation plans and/or asset maintenance if necessary;

Communicate more accurately with manufacturers, understand the behaviour of assets of different manufacturers in specific technical locations;

Support decision-making processes in future investments in assets, or in extension of the life of these.

Methodology.

The methodology requires an important number of input data to the index calculation models, such as the ones mentioned below:

The identification of the asset, which includes the category of the equipment under study, the current age, the expected life, the name of the manufacturer, the model of the equipment and the location of the installation.

The operation data recorded during a certain period of time, which combined conveniently allows us to know the time that the equipment has been working on stress, number of starts and stops, consumption, etc.

The condition of the equipment, that is, the results of the analyses performed on the equipment in site, results of readings of physical variables such as temperature and vibrations, results of visual inspections, thickness measurements, thermography, etc.

Development.

The application procedure for calculating the health index is based on 5 consecutive steps, in which, starting from an estimated normal life associated with an equipment's category, a current health index is reached. For this, a series of factors related to the location, operation and condition of the asset are considered.

It is presented in the following Figure 1, the model, with the 5 steps for calculating the health index of an asset.

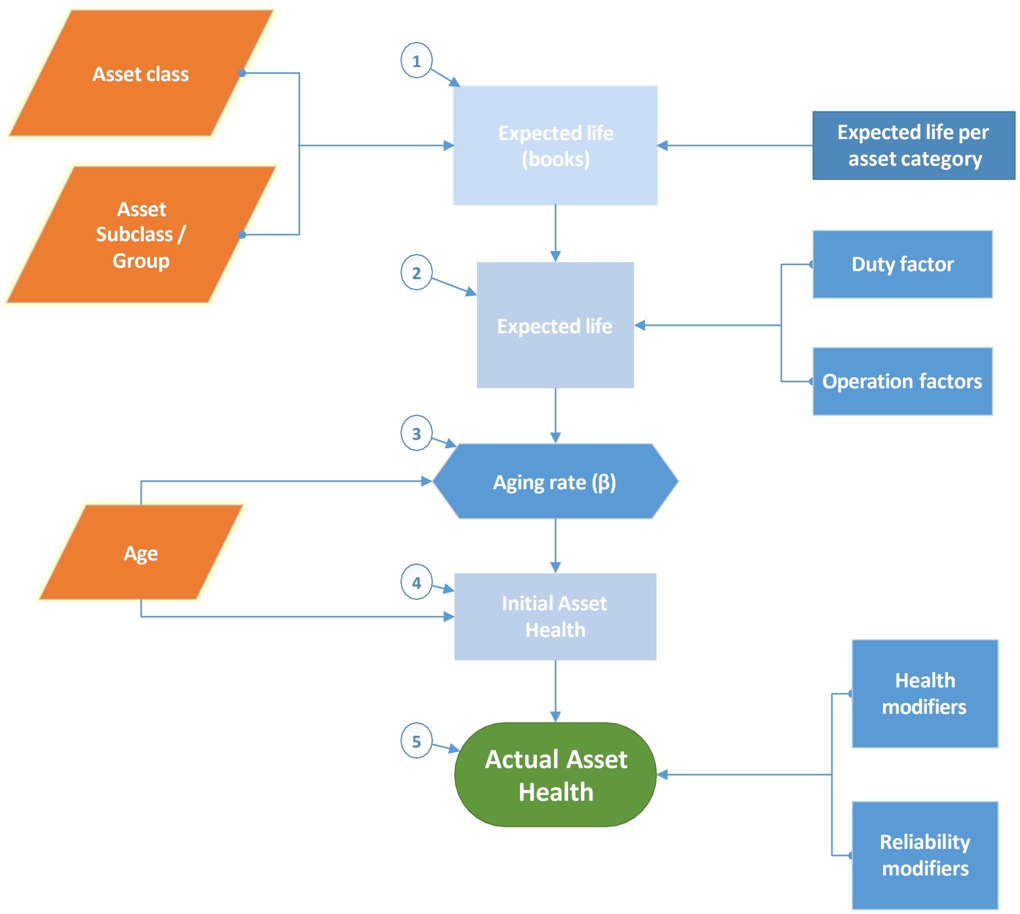

Figure 2. Procedure to calculate the AHI.

Step 1. Asset's selection, definition of category and sub-category. Capture of UT data, physical asset, and obtaining the estimated normal life of the asset.

In this first step, the identification of the asset and all the information related to the functional location, such as:

Functional location of the location in the plant management system where the equipment is located.

Inside / outside situation of the asset. This parameter will be considered to determine the exposure to external agents that may affect the health of the asset.

The distance to the coast. This parameter will be taken into account, like the previous one, to know the possibility that the humidity and the corrosive environment due to being close to the coast, may cause damage to the health of the asset.

Average outside temperature. It is understood by the average of the exterior temperature, at the average annual temperature registered in the site and that can directly affect the performance of the equipment located there.

Exposure to agents such as: dust in suspension and corrosive atmosphere. The proximity of the facilities to industrial emission sources of dust in suspension and corrosive agents, can cause the acceleration of equipment deterioration in the long term.

Regarding the equipment information, we identify manufacturing data, model and technical design specifications for the preparation of tables that will be used later in the definition of health modifying parameters.

The estimated normal life of the asset is a data that, in general, comes from the technical direction of the company, considering the experience accumulated so far and the information provided by the different manufacturers.

The value of the estimated normal life is used as a starting point for the realization of all the calculations that will be seen below. Keep in mind that its value is approximate and only depends on the asset category. As we will see below, it will be modified by the characteristics of the location and loading.

Step 2. Impact's evaluation of load and location factors by type of asset, technical location and estimated life expectancy.

Compiled all the information in the previous point, we proceed to the evaluation of the location and load factors (unambiguously associated with the technical location of the asset, as discussed previously). Since there is more than one variable that affects each one of the factors, for each of them a single combined factor must be calculated. Next, its obtaining is shown.

Depending on whether the asset is inside or outside a compartment that protects it from external agents, there are two ways to estimate it. If the technical location of the asset is external, the calculation of the combined factor of location is calculated following the equation shown below.

FE: Combined location factor.

FDC: Distance to the coast factor.

FA: Altitude above sea level factor.

FT: Annual average of outside temperature.

FAT: exposure to corrosive atmosphere factor.

FPS: exposure to dust in suspension factor.

In this case, being an element on the outside there is some factor greater than one (Fi ≥ 1), being Fi any of the factors contemplated above:

= max (FDC, FA, FT, FAT, FPS)

The load factor (FC), as well as the location factor, is inherent in the technical location. This factor measures the load request that is made on the equipment in that location, in front of the maximum admissible load. Normally, this data is obtained from the start-up and delivery of the equipment by the manufacturer, being recorded in the technical specifications of the equipment. In general, the following equation is used:

The Estimated Life of the asset is the quotient that results from dividing the estimated normal life obtained in the previous section, between the product of the location and load factors.

Therefore, depending on where the asset is located, and its expected level of performance, its useful life can be modified.

Step 3. Calculation of the aging rate.

A fundamental hypothesis of the chosen methodology is that the aging of an asset has an exponential behaviour with respect to its age. The aging rate is the parameter of the model that allows us to express mathematically this mode of behaviour, and take into account the different phenomena that the asset can suffer throughout its useful life, such as corrosive phenomena, wear, oxidation of oils, breakage of insulation, etc.

The aging rate (β) is determined by the natural logarithm of the quotient between the health corresponding to the new asset and the health it would have when it reaches the estimated life. The equation for its calculation is the following:

:	Asset aging rate.
Estimated life:	Time calculated in the previous section.
HI new = 0,5	Health value corresponding to a new asset;
HI estimated life =5,5	Value of health corresponding to their estimated life time;

Step 4. Obtaining the Initial Current Health Index.

The health index, as previously discussed in the definitions section, is a dimensionless number between 0.5 and 10, with an exponential behaviour with respect to the age of the asset, which is characterized by the aging rate of this.

For the calculation of the initial current health index (HIi) of an asset is used the following equation, where the age of the asset is the current age (in units of time) and the aging rate β is calculated in step 3.

According to the available data we obtain the value of β, as well as the initial value of the health index.

Step 5. Evaluation of the impact of health modifiers, reliability and calculation of the Current Health Index.

The current health index (AHI) is the result of the adjustment of the initial current health index, obtained in step 4, using health and reliability modifiers.

For any asset, the current health index will be determined by its status, operating conditions and reliability conditions at the time of evaluation. For the determination of the current health index, the following equation is used:

Where,

HIi: initial current health index.

MS: modifier of the health of the asset (condition and operation).

MF: reliability modifier of the asset.

For the evaluation of the health modifier (MS) that appears in this last equation, the different variables that are possible to measure and quantify that constitute the health modifiers that affect the equipment are taken into account, as well as the weights that will affect to each of the variables.

For the reliability modifier, depending on the category of asset, model and manufacturer, the value of this parameter is determined.

In general, the equations to obtain the value of the health modifier (MS) and the reliability modifier (MF) will be the following:

Where,

j=1…n index used for different health modifiers,

MSi (age): health modifier in time of age.

Where,

k=1…m index used for different reliability modifiers,

MFi (age): reliability modifier in time of age.

In this way, a graphic representation of the evolution of the health index can be obtained for each of the subsystems of an asset, where the degradation speed of each of them is different, which leads to the planning of large maintenance to throughout the life cycle of the asset. Figure 2.

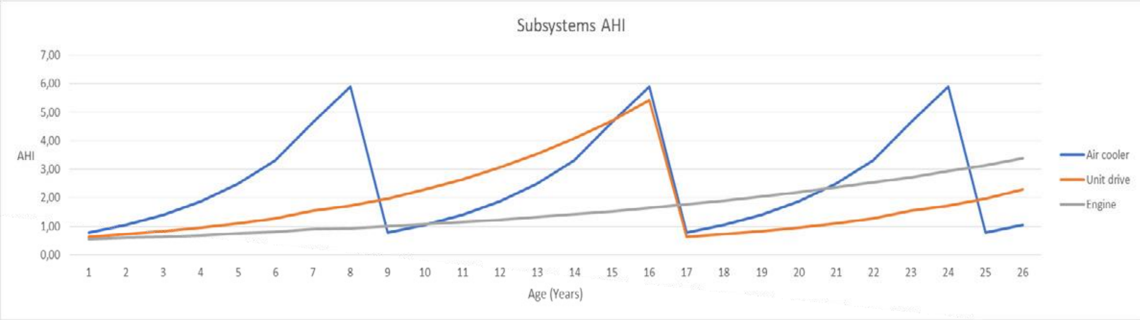

Figure 2. Health index for the different subsystems of an asset.

Interpretation of the value of the Output Index.

The first range is between the values AHI = 0.5 and AHI = 4. The behaviour of the equipment in this range is similar to that of a new equipment.

The second range, which is comprised between the values AHI = 4 and AHI = 6, corresponds to the period of time in which the first symptoms of wear on the equipment begin to appear. In this range, the value corresponding to AHI = 5.5, is the value of the health index equivalent to the normal life expected for the type of equipment under study, as well as each subsystem thereof.

From this period, three intervals are contemplated in the methodology as the AHI index exceeds the values of 6, 7 and 8 respectively.

The methodology assumes that exceeded the value of AHI = 8, the equipment is at the end of its useful life.

The following table (table 1) shows the different ranges of the health index. In this case, it corresponds to an asset with a normal life expected of 50 years, so the remaining life is adjusted to this particular case. On the other hand, the recommendations for action can be applicable to any specific equipment case.

AHI	Condition	Expected Lifetime	Requirements
4 - 0.5	Very good	More than 15 years	Normal maintenance
6 – 4	Good	More than 10 years	Normal maintenance
7 - 6	Fair	From 3 – 10 years	Increase diagnostic testing, possible replacement depending on criticality
8 - 7	Poor	Less than 3 years	Start planning process to replace
10 - 8	Very poor	Near to the end of life	Immediately assess risk; replace or rebuild based on assessment

Table 1. Asset Health index and expected lifetime.

Process pumps fleet application to support maintenance and replacement strategies.

An example of application of the methodology is the case of a fleet of process pumps that are part of the critical systems of a plant. The functional loss of any of these pumps can result in unacceptable situations for the business, such as plant shutdowns, production losses or some type of impact with associated industrial or environmental damage.

In order to establish the appropriate operation scenarios, the plans for major maintenance and equipment substitutions are made based on the health index and not depending on the hours of operation as usual.

In this case, the MS and MF variables that are taken into account for the model are shown in the following table (table 2)

Measurable Variable	Health modifier))MS	Reliabilty)modifier (MF	Score
Vibration analysis	x		0.5
Thermal jump between inlet and output of the pump	x		0.5
Power consumption	x		0.4
nº start-up/shutdowns	x		0.25
nº of alarms & shots due to low intake pressure	x		0.25
)Speed)rpm			0.25
Fluid leaks			0.25
Oil analysis			0.2
Motor isolation analysis			0.2
Number of corrective maintenances		x	0.2
Inactivity of the pump		x	0.15
Number of overhauls		x	0.1

Table 2. Health & reliability modifiers (MS, MF) for process pumps.

The score obtained for the critical process pumps fleet (figure 3), appears ordered from lowest to highest AHI. Pumps with a lower AHI (H <4), which are in the left area of the graph, have a condition and a failure rate that can be similar to that of a new equipment. On the other hand, pumps with a higher health index (H> 4) begin to behave like more aging equipment in which their failure rates begin to increase and consequently, the associated risk increases from the point of criticality.

The size of each circumference indicates the difference between the initial health index (HIi) and the health index (AHI). Circumferences with larger size indicate that the aging of the equipment has been greater than expected, so it will be necessary to pay more attention to these equipment and increase surveillance. The number that is inside each of the circles indicates the number of overhauls that have been made to the equipment.

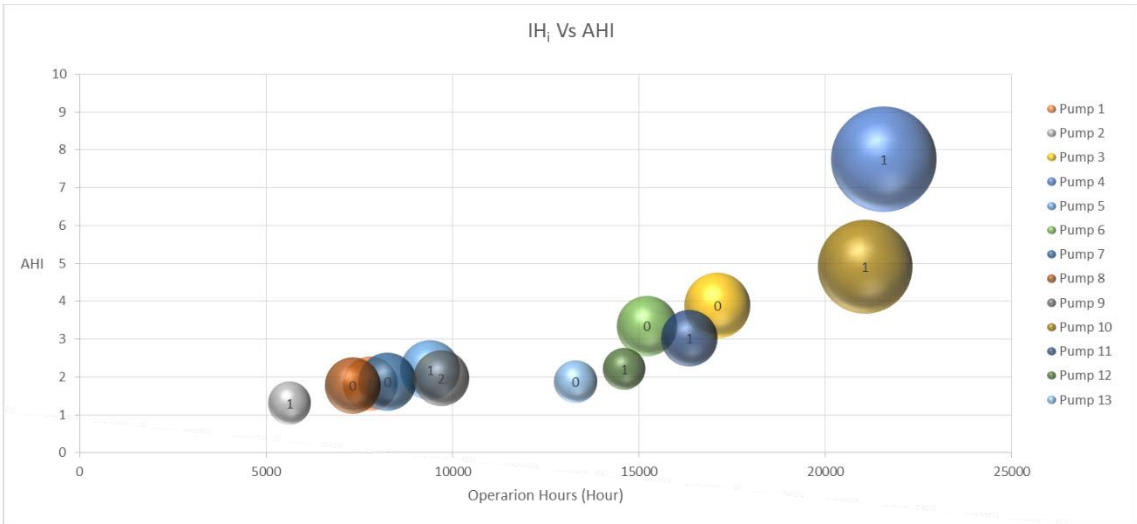

Figure 3. HIi VS AHI for a process pumps Fleet

For those pumps in which the AHI has exceeded 5.5 points, it is necessary to consider major repair or replacement in relatively close periods, including stopping operations until a deep diagnosis has been made to rule out possible problems during its functioning. In the example, pumps 4 and 10 should stop operating and raise the overhaul or replacement. Pump 11 with more hours of operation than pump 6 (17000 vs 15000) has a lower aging (AHI = 3.5 vs AHI = 4.1). This is because the load to which the pump is subjected and the results of the variables of the health modifiers are less aggressive in 11 than in 6. Probably, if the operating and contour conditions do not change, the overhaul of pump 11 will be carried out later (greater than 20000 hours of operation), however, pump 6 will have to be done before the manufacturer's recommendation.

Conclusions.

Today, the use of tools for decision making about long-term renewal and replacement of equipment for organizations is quite extended. Thanks to life-cycle cost analysis (LCC), it is possible to know from an economic point of view, the cost of an asset over its useful life and to estimate the time for replacement if needed. The disadvantage in many cases, is the large amount of variables that must be handled when estimating the real cost of an asset over its useful life, generating a scenario of high uncertainty. At that moment, it is where the AHI comes into play as a support tool, having a completely different calculation methodology, estimated from lab tests in order to know the asset condition, visual inspections, operation and maintenance history and the age of the equipment and its components. Using asset health index offers a lot of advantages, such as, provide an approaching indication of the asset at the end of its useful life, prediction of long-term needs replacement in large volumes of assets, identifying potential peaks with investment requirements, identify problems, risks and opportunities for maintenance management, etc.

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Vibration Condition Monitoring and Data Management in A Modern Waste Recovery Park

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Abstract

Vibration condition monitoring and data management in a modern waste recovery park conjures up images of pages and pages of datasheets, with hundreds of measurement locations and millions of data points. This paper aims to prove that the whole process can be simplified and operated as a practical, cost effective solution without overcomplicating or overprotecting machinery, whilst ensuring the plant is maintained in an effective manner. Moreover, using the strategies and methodologies adopted; including targeted vibration monitoring, high resolution data analysis and concise data management techniques ensures lengthy and expensive breakdowns are minimised.

Keywords: Vibration, Rotating, Maintenance

Introduction

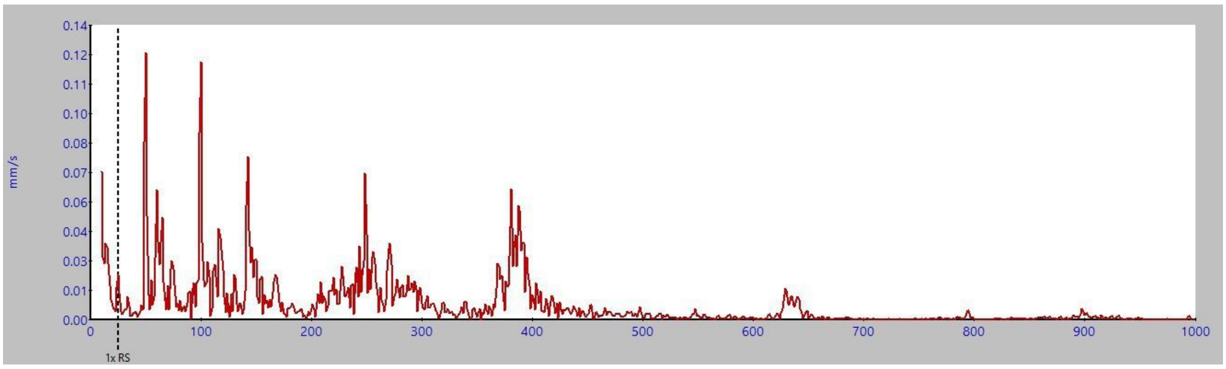
A large state-of-the-art waste recovery plant in the United Kingdom combines waste recycling with renewable energy generation. The plant includes a mechanical treatment facility for waste recycling, an anaerobic digestor and Combined Heat and Power generators (CHP) for energy from biodegradable waste and an Advanced Thermal Treatment facility that uses non-recyclable and non-compostable waste as fuel to heat steam and power an 8 MW turbine. The plant has over 250 machines with rotating parts (motors, pumps and fans) that require constant monitoring. Vibration condition monitoring is a non-invasive technique of monitoring the condition of the machines and identifying faults before they become failures. However, the large amount of measurement data requires significant data management skills. Rotating Equipment Verification Limited (REV) have carried out baseline measurements of the equipment, set up a management scheme and provided training to the employees of the waste recovery park so that they can continue carrying out periodic monitoring. The potential of identifying faults before they cause failures and therefore, potentially a complete plant shutdown, leads to massive savings for the waste recovery site operator.

The initial baseline measurements incorporated a significant amount of data, culminating in the output from the measurement software [5] which had up to thirteen graphs per measurement location, including ISO spectra, g- spectra, separate spectra for displacement, unbalance, misalignment and looseness, time waveform, trend line for ISO, BDU and g. Multiplied by three measurement directions per machine and by all machines, this gives an unmanageable amount of data. Expert knowledge was required to carry out data selection and export only data that was relevant to the vibration pattern of the machine. The summary report of pre-selected data still ran into a three hundred and thirty four page report – see Appendix 1 showing an excerpt of one of the many summary tables.

Vibration condition monitoring

Vibration monitoring is an non-invasive method of checking machine condition. An ideal machine has smooth rotation with the centre of mass of the rotating element located exactly at the centre of gravity. In that case there would be minimum or no vibration levels recorded. In reality, there is always some degree of unbalance, which causes vibration at a frequency corresponding to the rotational speed. Vibration levels depend on the magnitude of the exciting force, and the mass, stiffness and damping of the elements. A machine in excellent condition will show very low vibration levels (< 1 mm/s rms). The frequency spectrum will either show broad band low- amplitude noise floor or a single peak at the rotational frequency - see examples below:

a)



mm/s

b)

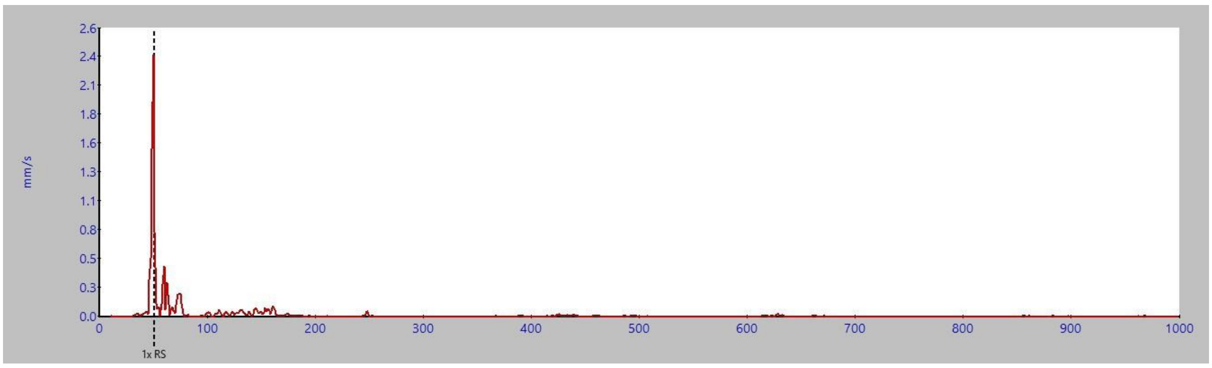


Figure 1 – Two spectra graphs of machines in good condition displaying: a) low amplitude noise floor across the frequencies, b) single peak at rotational speed without harmonics

Damage and wear and tear of the machine will inevitably cause an increase in vibration levels. However, only measuring the magnitude of vibration can be inconclusive, unless the measurements are regularly repeated and a trend line is plotted to show how the magnitude increases over time. Another useful tool is FFT (fast-fourier transform) analysis [4], which allows us to look at the frequency spectrum (examples shown in Figure 2). A large peak at the fundamental frequency may indicate unbalance. Visible harmonics may indicate different problems, e.g. misalignment at 2 x F0, looseness at multiple higher harmonics. Gear mesh, bearing or fan blade problems can cause vibrations at much higher frequencies (> 1000 Hz) [3 &4], dependent on numbers of teeth, numbers of balls/rollers or number of fan blades for example.

The graph below shows a spectrum with clearly visible harmonics up to 5 x F. Although the overall velocity levels are low, the spectrum indicates likely looseness, which could lead to increased vibration in the future (growing trend line), which would increase looseness and can lead to eventual failure.

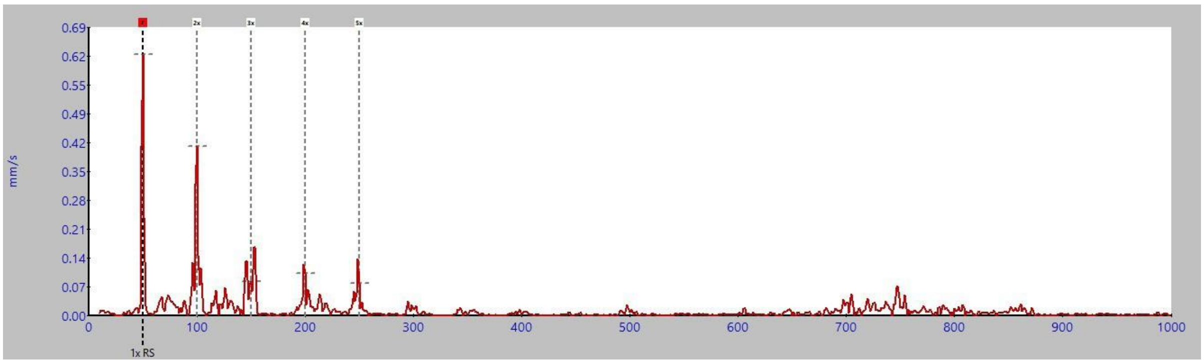


Figure 2 – Spectrum of a pump motor vibration with clearly visible harmonics.

Faults can be detected using a combination of the following methods:

- Comparison of overall levels to industrial standards (ISO 10816-3);
- Comparison with previous measurements (trend line analysis);
- Spectrum analysis;
- Time waveform analysis;
- Phase analysis.

With the exception of phase analysis, the instrumentation used on this project, a TPI 9080 Pro meter and VibTrend software [5], allowed the use of the above methods.

ISO 10816-3 [2] is the current standard for the evaluation of “standard” rotating machine operating condition. Issued in 2009 it covers “large and medium size industrial machines with nominal power rating above 15 kW and nominal speeds between 120 rpm and 15000 rpm”. In addition, pumps are added as a specific category for consideration. This range covers most rotating machines and can therefore be used as a good guide for in-situ operating conditions. The chart below illustrates the standard and allows a quick comparison of actual against standard operating condition. Variations will inevitably occur when comparing these standards to actual machine operating conditions. Machines should not however be condemned because of variations in readings without first considering other potential reasons for the difference in readings. The values in the chart are therefore used as guidelines, but are used in combination with spectrum analysis and trendlines to determine the condition of a machine.

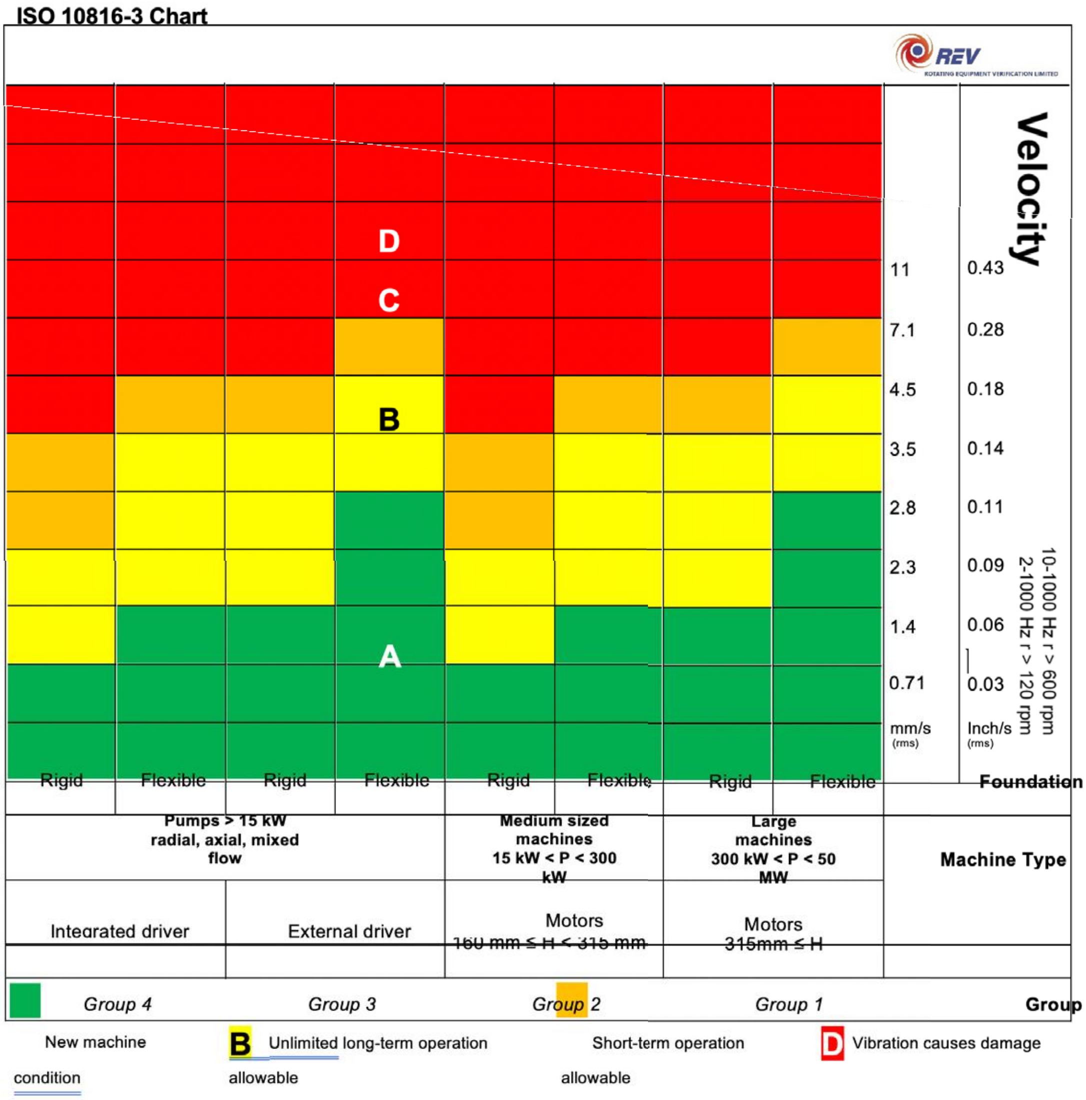


Figure 3 – ISO 10816-3 chart

Definitions

Vibration - Repeated oscillating movement in alternating directions.

Amplitude - Magnitude of vibration expressed either in terms of the peak value, peak-to-peak or the energy equivalent average called RMS (Root-Mean-Square)

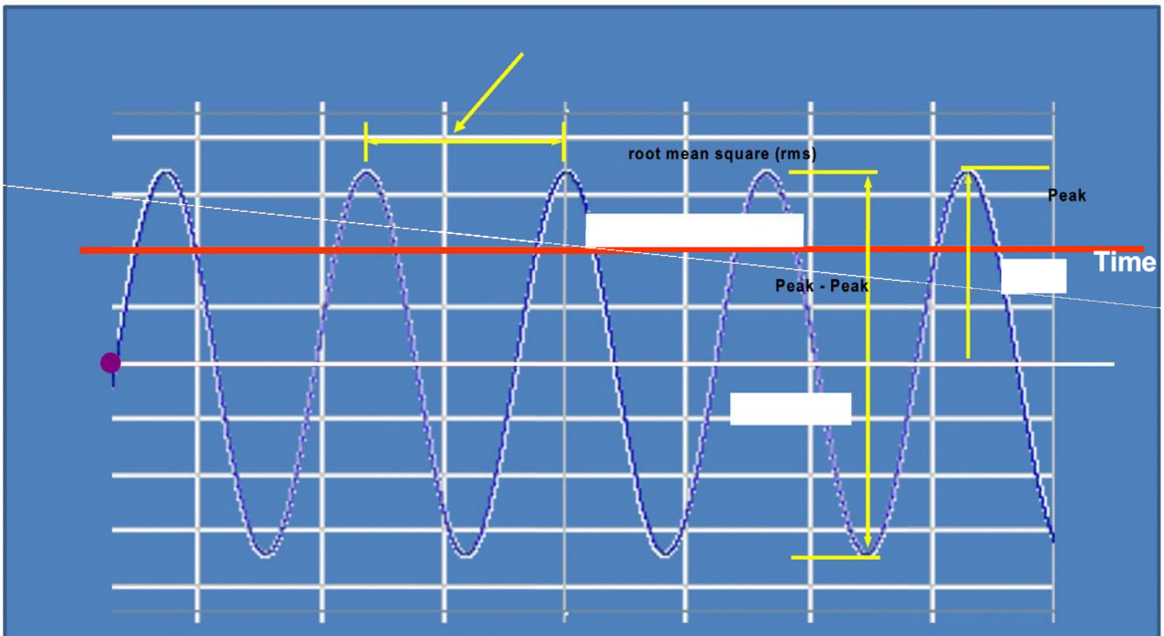


Figure 4 – Example of a simple vibration plot

Displacement - Physical movement of the vibrating element measured in millimetres (mm) or mils

(thousandth of an inch). Usually the peak-to-peak displacement is measured.

Velocity - Speed at which displacement occurs. Usually measured in mm/s RMS or inch/sec RMS. Acceleration - The rate of change of velocity. Usually measured in m/s2 or g values (gravitational

constant)

Frequency - The number of oscillations in a given time. The commonly used unit is Hz, where 1 Hz =

1 oscillation in 1 second. F = rpm / 60 [Hz]

Fundamental frequency - The lowest frequency of vibration, usually corresponding to the rotational speed. If the rotational speed is expressed in rpm (revolutions per minute), then the fundamental frequency, in Hz, can be calculated by dividing the rpm by 60.

Harmonics - Vibrations that occur in frequencies that are multiples of the fundamental frequency, e.g.

2xF, 3xF, etc.

Frequency spectrum - A plot showing vibration levels at different frequencies in a wide range. Useful in condition analysis, as different frequencies can correspond to different types of faults, e.g. unbalance, gear mesh damage, bearing damage, etc.

ISO (mm/s) - Vibration levels expressed as rms velocity in the range of 10-1000Hz, in line with ISO

10816-3:1998

g - Vibration total acceleration (m/s2) expressed in g units (1g = 9.81 m/s2, i.e. Earth gravitational constant).

BDU - 'Bearing Damage Units' – vibration units derived from g rms acceleration above

1000 Hz. 100 BDU corresponds to 1g rms above 1kHz. This unit is an indication of likely bearing damage.

4. Methodology

Measurements were carried out using a single axis accelerometer with a magnetic mounting block. A minimum of three measurements were carried out on a single machine, to get three orthogonal directions: vertical, axial and transverse (see Figure below). This simplified instrumentation approach was adopted to ensure the monitoring could be continued by the client's own plant operators in the future, therefore more specialised and complicated instrumentation was undesirable.

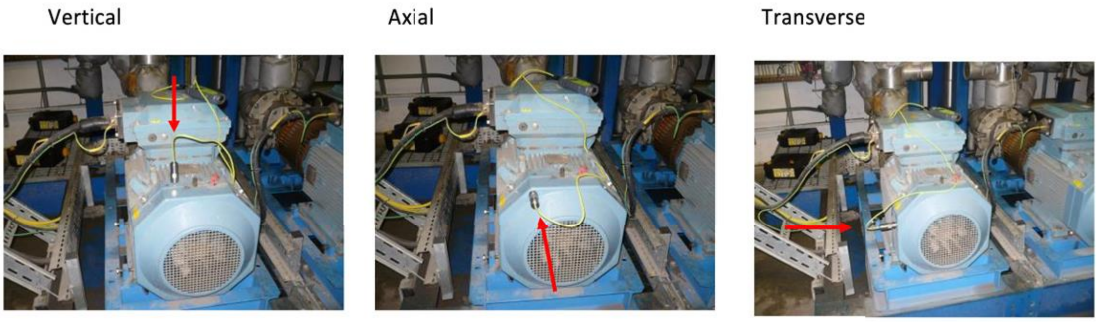


Figure 5 – Photographs showing standard vibration points

Choosing the measurement location was a challenge. Many of the machines are pumps with integrated motors, therefore different vibration levels will occur on the non-drive end, drive end of the motor, the bearing and on the pump housing. However, with over 250 machines and a scheme for plant operators to carry out regular monitoring themselves, the aim was to streamline the process and choose one common location for most of the machines. For most units, the non-drive end of the motor was the easiest or only accessible location for accelerometer placement (as shown in Figure 5). It is not considered to be the textbook location, but it allowed to have a consistent measurement procedure for all machines. Where vibration (and often noise levels) were high and further investigation was required, then additional measurement points were added on the drive end, bearing and pump.

For each measurement point, a 3-second steady-state RMS velocity and acceleration measurement was recorded. The frequency range of the TPI 9080 meter was 2-10000 Hz. FFT analysis was carried out using VibTrend software [5].

Overall ISO velocity values were used to compare against ISO 10816 [2], however, the limits are used as guidelines only. Comparative analysis, trend lines and FFT analysis were used to determine the condition of the machines.

It was important to determine the rotational frequency (RPM) of the motor, as the relation between spectrum peaks and the RPM can give an indication of the likely fault. According to well established industry guidance [1, 3 & 4] the following list shows links between vibration frequency and its likely cause:

- F0 – Imbalance;
- 2 x F0 – Misalignment, bent shaft;
- 3 x F0, 4 x F0, 5 x F0, etc. – looseness;
- High frequency (>1000Hz) – bearing damage, propeller damage, fan blade damage.

Where; F0 - fundamental frequency, Hz - (F0 = RPM ÷ 60).

Examples of spectra indicating likely causes of vibration are shown in Figure 6 below.

The spectra are plotted in terms of velocity (mm/s) for low frequency (10-1000 Hz) and acceleration (g) for high frequency (10-10000 Hz).

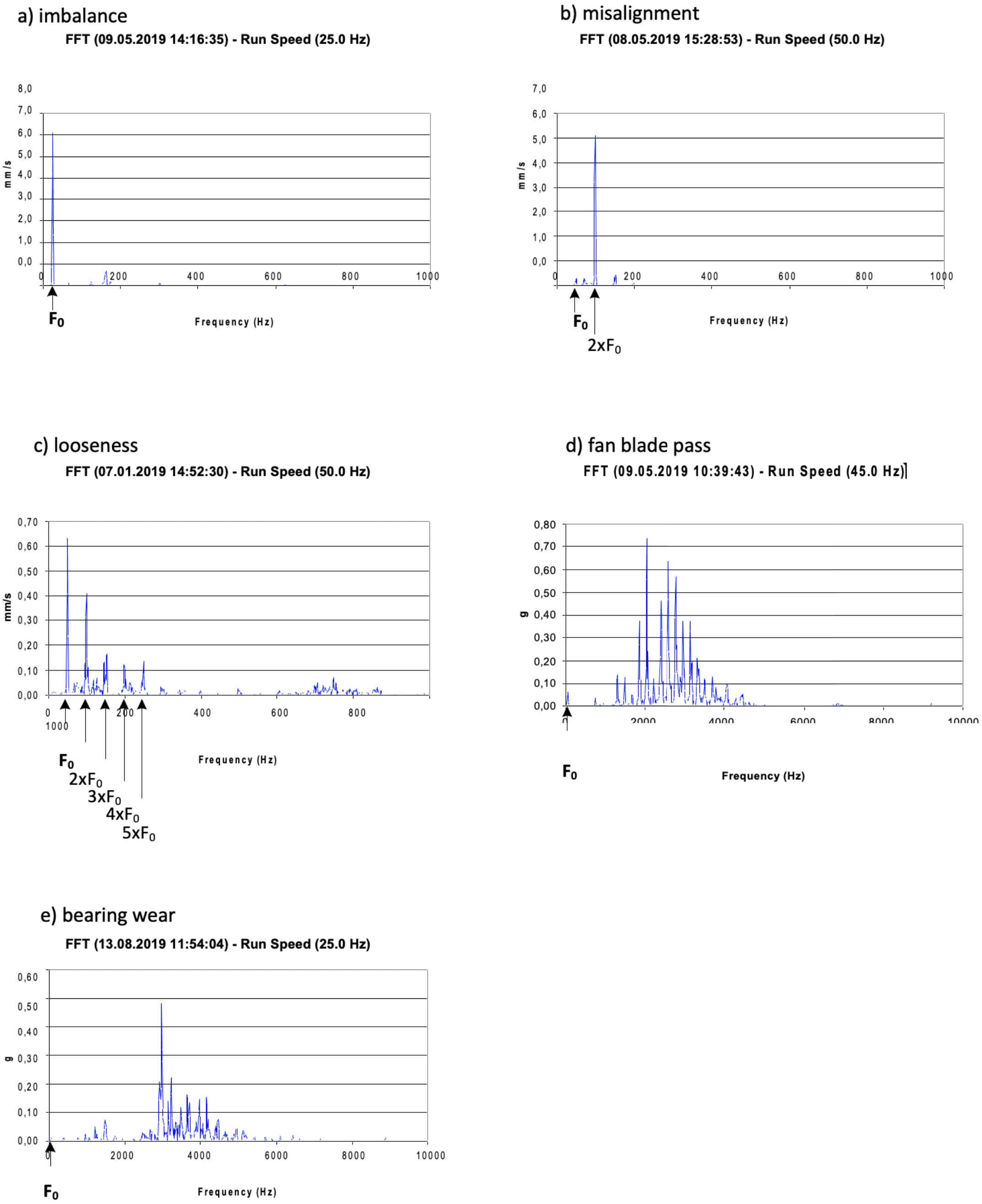


Figure 6 – Spectra indicating different causes of vibration

5. Results

Throughout the baseline measurement process, 261 machines were identified and catalogued. 179 were measured. The following is the outcome of the measurements:

- 147 were deemed in good condition. A recommendation to continue periodic monitoring and observe trend lines was given.

- 24 machines had vibration levels that indicated some condition problem. A warning label was given and it was recommended that either measurement is repeated at different locations (e.g. pump or bearing), trend lines are observed or that the unit should be serviced at the earliest opportunity.

- 8 machines had high vibration levels indicating likely failure was imminent. A critical warning level

was given and a recommendation to investigate further and / or service unit was advised.

The practical outcome of the baseline measurement exercise was that a fault was found in two critical machines (thermal oil pump and coolant medium pump) and the units were replaced before they failed and potentially caused a costly shutdown of the plant. One of two bearings on the thermal oil pump was causing high g levels around

3000 Hz. The replaced unit shows negligibly low levels – see Figure 7. The coolant medium pumps required some engineering in addition to replacing the units. They are mounted vertically on a metal support frame – see Figure

8. Such a mounting makes the motor vulnerable to resonant vibration of the support frame, which coincided with the rotational frequency. Therefore, stiffness had to be added to the frame. Measurement results before and after replacement and frame improvement are shown in Figure 9.

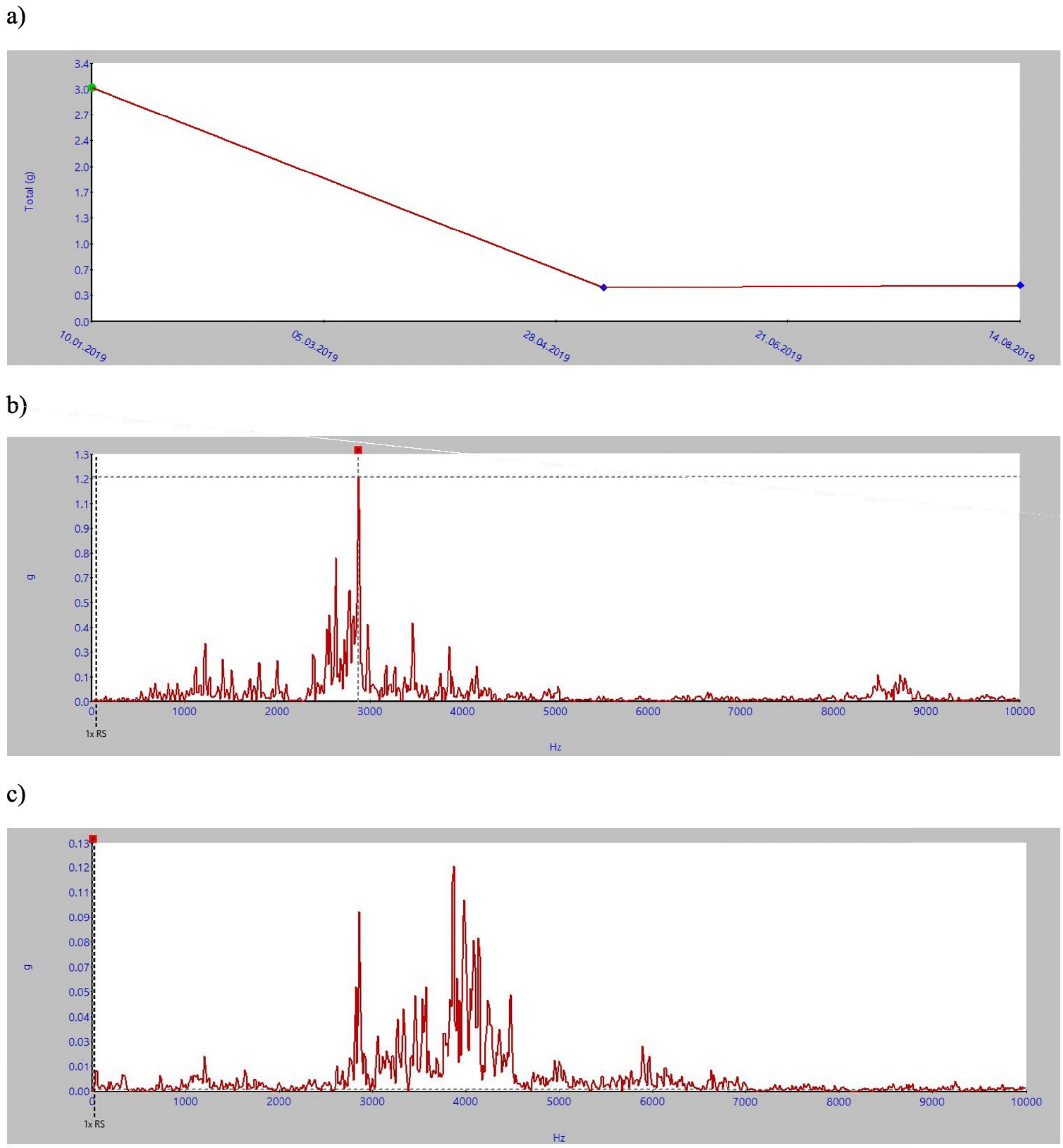


Figure 7 – Acceleration (g) measurement results on a thermal oil pump that was replaced

a) Trend line of g-values - overall vibration dropped from 3.0 g before service to 0.5 g after service b) g spectrum before service - large peak at 2875 Hz indicated problem with one of the bearings.

c) g spectrum after service, on replaced unit - with new bearings, negligible vibration around 0.12 g.

a) b)

Figure 8 - Coolant medium pumps: a) old unit; b) new unit on improved support frame

a)

b)

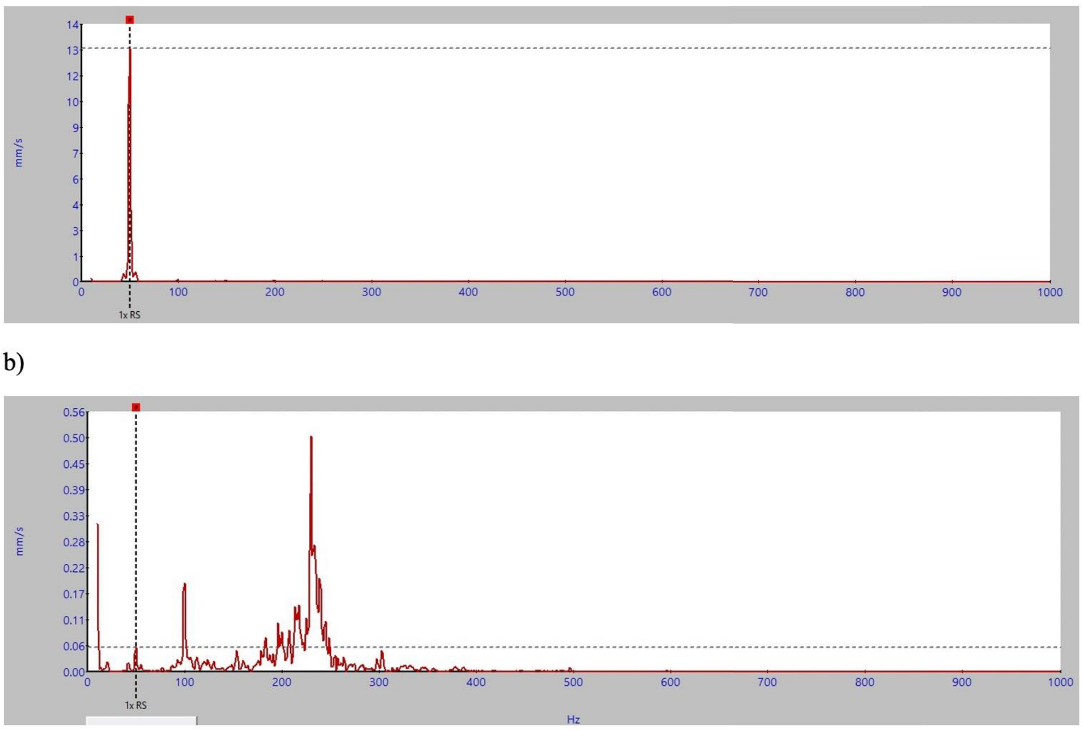


Figure 9 - Velocity spectrum on coolant medium pump motor: a) before service - large peak at rotational frequency indicates unbalance and was caused by resonant vibration of the support structure, coinciding with the rotational frequency; b) negligible vibration after unit replacement and adding stiffness to support frame.

6. Conclusions

Baseline vibration condition monitoring was carried out on a waste recovery plant. The baseline monitoring lasted for approximately 10 working days with one engineer carrying out the measurements. In line with the scheme, plant operators will take over and carry out periodic measurement of all plant, preferably on a one-month or three-month basis. The baseline measurements already showed problems in some key areas thus potentially saving on unnecessary shutdowns. Seven plant operators were trained to carry out monitoring, manage the database and interpret the results. During a practical training session, they already found a bearing problem on another thermal oil pump. This confirms the importance of periodic monitoring. Upon learning the measurement procedure and data analysis basics, the operators themselves commented that this scheme will bring great savings to the plant.

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Appendix 1 - Excerpt of a Summary Table

Identification	Machine	Serial Number	RPM	Highest ISO (mm/s)	Highest bearing noise (BDU)	Status	Comments	Recommendation
[illegible]	Conv. motor	[illegible]		21.3	37	Warning	Extremely high ISO levels indicates significant unbalance	Service at earliest convenience
[illegible]	Conv. motor	[illegible]		-	-	-	Out of reach. Not measured	-
[illegible]	Conv. motor	[illegible]		2.8	2	OK	Good condition	Observe trend lines
[illegible]	Brush motor	[illegible]	1461	4.1	53	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]	1460	4.4	6	OK	Good condition	Observe trend lines
[illegible]	Sort drum motor	[illegible]		-	-	-	Out of reach. Not measured	-
[illegible]	Sort drum motor	[illegible]		-	-	-	Out of reach. Not measured	-
[illegible]	Conv. motor	[illegible]	1455	3.8	14	OK	Good condition	Observe trend lines
[illegible]	Brush motor	[illegible]	1500	15.8	9	Warning	High ISO levels are characteristic for brush motors, however, condition of motor should be checked	Observe trend lines / service at earliest convenience
[illegible]	Conv. motor	[illegible]		3.0	9	OK	Good condition	Observe trend lines
[illegible]	Brush motor	[illegible]	1320	3.2	30	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]	1455	3.6	29	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]	2028	5.9	9	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]	2478	4.5	72	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]	1278	12.2	3	Warning	Significant vibration peak at 230 Hz, possibly unrelated to the motor condition	Observe trend lines and compare spectra after next measurement
[illegible]	Conv. motor	[illegible]	1460	2.6	12	OK	Good condition	Observe trend lines
[illegible]	Rolling bar motor	[illegible]		-	-	-	Out of reach. Not measured	-
[illegible]	Conv. motor	[illegible]	2328	9.9	3	Warning	High ISO values indicate likely unbalance	Observe trend lines / service at earliest convenience
[illegible]	Conv. motor	[illegible]	2928	5.7	19	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]	1800	3.1	3	OK	Good condition	Observe trend lines
[illegible]	Eddie current motor	[illegible]	1800	23.7	12	Critical	Extremely high ISO level and rich harmonic content in spectra indicate likely significant looseness	Service
[illegible]	Conv. motor	[illegible]		3.7	9	OK	Good condition	Observe trend lines
[illegible]	Sorting drum motor	[illegible]		-	-	-	Out of reach, not measured	-
[illegible]	Sorting drum motor	[illegible]		-	-	-	Out of reach, not measured	-
[illegible]	Ballistic separator motor	[illegible]	1473	5.4	21	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]		-	-	-	Out of reach. Not measured	-
[illegible]	Brush motor	[illegible]		8.9	65	Warning	High ISO levels are characteristic for brush motors, however, condition of motor should be checked	Observe trend lines / service at earliest convenience
[illegible]	Brush motor	[illegible]		13.0	3	Warning	High ISO levels are characteristic for brush motors, however, condition of motor should be checked	Observe trend lines / service at earliest convenience
[illegible]	Conv. motor	[illegible]		-	-	-	Out of reach, not measured	-
[illegible]	Ballistic separator motor	[illegible]		3.4	15	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]		-	-	-	Out of reach. Not measured	-
[illegible]	Brush motor	[illegible]		-	-	-	Out of reach. Not measured	-
[illegible]	Conv. motor	[illegible]		4.0	19	OK	Good condition	Observe trend lines
[illegible]	Wind shifter motor	[illegible]	1455	3.1	5	OK	Good condition	Observe trend lines
[illegible]	Wind shifter motor	[illegible]	1455	2.3	11	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]		5.7	21	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]	1455	2.5	3	OK	Good condition	Observe trend lines
[illegible]	Conv. motor	[illegible]	1480	4.0	9	OK	Good condition	Observe trend lines

Graph Neural Networks for Traffic Forecasting

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Abstract:

The significant increase in world population and urbanisation has brought several important challenges, in particular regarding the sustainability, maintenance and planning of urban mobility. At the same time, the exponential increase of computing capability and of available sensor and location data have offered the potential for innovative solutions to these challenges. In this work, we focus on the challenge of traffic forecasting and review the recent development and application of graph neural networks (GNN) to this problem. GNNs are a class of deep learning methods that directly process the input as graph data. This leverages more directly the spatial dependencies of traffic data and makes use of the advantages of deep learning producing state-of-the-art results. We introduce and review the emerging topic of GNNs, including their most common variants, with a focus on its application to traffic forecasting. We address the different ways of modelling traffic forecasting as a (temporal) graph, the different approaches developed so far to combine the graph and temporal learning components, as well as current limitations and research opportunities.

Keywords: graph neural networks, traffic forecasting, deep learning

Introduction

The world's urban population will increase from 4.2 billion to 6.7 billion by 2050 as estimated by the United Nations [1]. In spite of the accompanying social evolution and benefits, the rapid rate of urbanization has significant social, economic and environmental costs associated, including air and water pollution, unsustainable energy consumption, toxic waste disposal, inadequate urban planning, decreased public health and safety, social vulnerability and community disruption. Notably, the mobility of passengers and freights in most large cities of the world is not yet sustainable. Urbanization has given rise to traffic congestion, increase of transports needs, ineffective accessibility, and reduced productivity. In particular, traffic congestion costs billions of dollars per year due to lost time, air pollution, and wasted fuel. In 2017, in the United States alone, traffic congestion induced a total of

8.8 billion hours of travel delay and 12.5 billion liters of extra fuel consumption, corresponding to a congestion cost of 166 billion dollars [2]. Efforts to develop solutions to the challenges brought by traffic congestion have focused on three avenues: championing transport alternatives, enlarging the infrastructure, and managing traffic flows [3]. While championing transport alternatives is mostly a public policy issue, and geographical and social constraints limit the increase of the size of infrastructure, the potential to efficiently manage traffic flows has increasingly become one important solution to traffic congestion. Today, the exponential increase of available data in cities and the growth of computing capabilities represents a crucial opportunity to tackle these challenges by leveraging innovative and integrated solutions. These include the development of intelligent transportation systems (ITS), smart vehicle sharing systems and home automation, and smart grids and energy solutions - all of which fall under the umbrella of the recent area of urban computing [4].

A core component of ITS is traffic forecasting. Its goal is to measure, model and predict traffic conditions in real-time, accurately and reliably, in order to optimize the flow and mitigate the congestion of traffic, and to respond adequately to other problems such as traffic light control, time of arrival estimates, and planning of new road segments. However, this is a very challenging problem due to several important factors. The successful forecasting of traffic conditions requires adequately handling heterogeneous data (e.g., integrating loop counter and floating car data) with complex spatio-temporal dependencies which are typically sparse, incomplete and high-dimensional. In addition, it requires computing in real-time and the inclusion of external factors such as weather conditions and road accidents.

This review is focused on the recent developments and applications of graph neural networks, a new family of deep learning models, to road traffic forecasting. In Section 2, we present a succinct history of traffic forecasting including traditional approaches and deep learning models that have had a great deal of success. Section 3 presents and discusses graph neural networks (GNN) and Section 4 reviews the literature of traffic forecasting based on GNN. W1e conclude, in Section 5, with a discussion of open challenges and research opportunities.

Traffic forecasting

W the weighted adjacency matrix. Denoting $X!!$ as the values of all the features of node i at time t, we aim to learn a function F that given a sequence of M historical time steps predicts the next N time steps:

$F([X!!!!!, \ldots , X!]; G) = [X!!!, \ldots , X!!!].$ (1)

Traffic data

Urban data can be classified according to their structures and spatiotemporal properties [9], as Figure 1 illustrates. We can distinguish datasets with respect to their spatiotemporal properties: spatiotemporal static data, spatial static but temporal dynamic data, or spatiotemporal dynamic data. They can also be classified with respect to their data structures in one of two types - point-based and network-based. In addition, urban data can also be classified according to its sources, such as geographical data, traffic data, and social network data, to name a few, and each of these can be further subclassified. Focusing on traffic data, this source can include loop detector data, floating car data, mobile phone data, call detail records, surveillance cameras, bike-sharing data, taxi records, mobile phone location data, parking records, and mobile apps' logs.

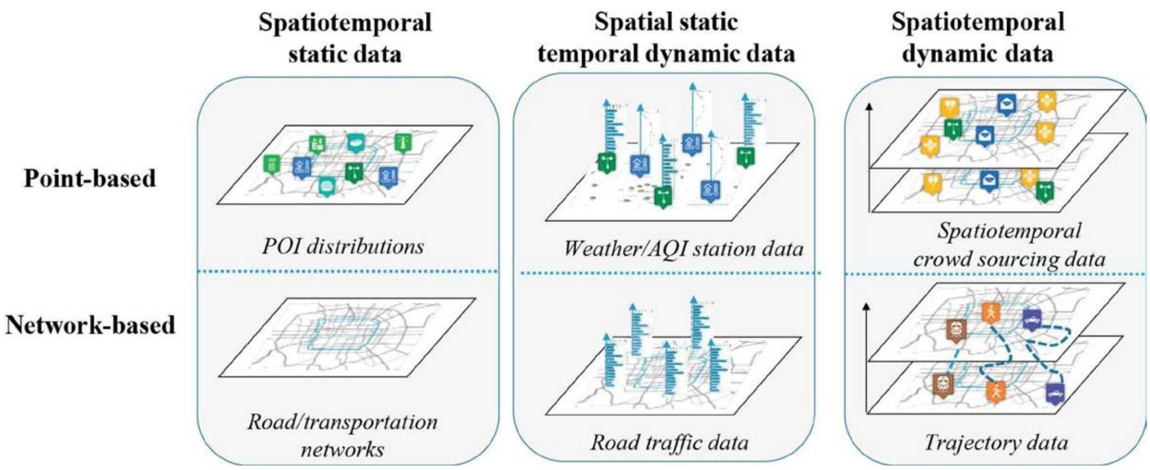


Figure 1: Six types of urban data [9]. Reprinted with permission.

Traditional approaches to traffic forecasting

In the last decades, traffic forecasting methods have been developed by researchers from different fields such as transportation systems [10], economics [11], statistics, and machine learning [12]. The methods can be divided into two categories: the knowledge- or model-driven approach and the data-driven approach. Knowledge-driven approaches usually aim at modeling and explaining the transportation network through differential equations and numerical simulation [13], [14]. Although the models can reproduce real traffic conditions fairly accurately, they require prior knowledge and detailed modeling, are not easily transferable to other cases, and require significant computational resources.

Traditional data-driven methods used in traffic forecasting can be divided into two categories: methods that do not model the spatial dependency and models that do model this dependency. The former category includes the Historical Average (HA) model, the auto-regressive integrated moving average (ARIMA) [15] and seasonal ARIMA (SARIMA) [16], K-nearest Neighbour (KNN) [17], support vector regression [18], hidden Markov models [19], among others. These approaches often require careful feature engineering and also rely on data to satisfy certain assumptions, such as stationarity. However, real data is often too complex and violates often these assumptions, leading in many cases to poor performance. Approaches that model the spatial dependency include Vector ARIMA, Spatiotemporal ARIMA and Spatiotemporal HMM [20]–[23]. Again, these methods perform poorly since they are not complex enough to model the non-linearity and non-stationarity of the data.

Deep learning approaches to traffic forecasting

Deep learning methods [24] are a class of machine learning methods that learn multiple layers of representations by composing increasingly more complex non-linear features on the upper layers by combining simpler features from the lower layers. This learning of complex representations is done mostly automatically and does not depend on a human doing manual feature engineering, which would require time and expert domain knowledge. In recent years, deep learning represents the state of the art in fields such as image recognition [25], natural language understanding [26], drug discovery [27], recommendation systems [28], and board and video games playing [29]. This success is mainly due to their representation power (as explained above) and to the fact that there exists an efficient method for training them (namely gradient descent through error backpropagation).

As in other domains, the application of deep learning methods to traffic forecasting has been very successful and has produced state-of-the-art results. Some of the earlier architectures did not model the spatial dependency, and used standard feedforward networks or deep belief networks [30] as well as recurrent neural networks such as long short- term memory (LSTM) and the gated recurrent unit (GRU) [31]–[33]. However, these models still fail to model the complex spatial dependencies that exist in traffic problems. Several models were proposed that aim at capturing these dependencies, using convolutional neural networks (CNN) [34] or a combination of CNN and LSTM [35], [36]. Still, since CNNs are mainly suited for data embedded in grid-line Euclidean spaces, they are not the natural architecture to real-world road networks. The next sections expand on how models using a graph neural network improved on these architectures.

Graph neural networks

The convolutional operator used in CNNs is very powerful but is limited to standard grid data, i.e., to data that originates in regular, two-dimensional, tri-dimensional, or higher-dimensional Euclidean spaces. Since various important machine learning problems involve tasks on graph structured data such as node classification [37] or molecule generation [38], researchers have developed a family of deep learning models that can leverage this inductive bias [37], [39]–[41]. These models are usually called graph neural networks (GNN) because they are neural networks that naturally handle graph data. In this section, we briefly review the area of graph neural networks and some of the most relevant works, and refer the reader to other reviews for more details and specific perspectives on this topic [41]– [46]. In Section 3.1, we categorize and describe several GNN models, and in Section 3.2 we list current open-source libraries for implementing GNNs.

Models

In this section, we describe several of the most relevant GNNs models developed so far. As shown in Table 1, we categorize GNNs into four main types, namely recurrent graph neural networks, convolutional graph neural networks, graph autoencoders and graph attention networks.

Category	References
Recurrent Graph Neural Networks	]50[–]47[,]39[
Convolutional Graph Neural Networks	]53[–]51[,]40[,]37[
Graph Attention Networks	]55[,]54[
Graph Autoencoders	]61[–]56[

Table 1. Categorization of graph neural network models and representative publications.

Recurrent graph neural networks

Extending previous work [62], [63], the Graph Neural Network model (GraphNN) [39] was the first neural network model that could process general types of graphs (eg, directed, undirected, cyclic, or acyclic). The fundamental concept of the GraphNN model is that every node v can be represented by a low-dimensional state vector h!and be defined by its features and by its neighbours based on an information diffusion mechanism from every node to its neighbors. The goal is to learn this representation which can be fed to an output function g, called the local output function, resulting in an output value or label $o\boldsymbol{v}$, for regression or classification, respectively. The model also defines the local transition function f, a parametric function, to be learned alongside g - both shared by all nodes. Together, these node representation and output are defined as:

$h! = f(x!, x!"[!], h!"[!], x!"[!]),$ (1)

$\boldsymbol{o}! = g(\boldsymbol{h}!, x!),$ (2)

where $x!$, $x!"[!]$, $\boldsymbol{h}!"[!]$, $x!"[!]$ are the features of v, the features of its edges, and the states and features of its neighborhood, respectively.

Denoting the vectors constructed by stacking all the states, all the features, all the node features and all the outputs by

$H, X, X!, O$ equations (1) and (2) can be rewritten compactly as

$H = F(H, X),$ (3)

$O = G(H, X!),$ (4)

where F and G are the stacked versions of f and g for all nodes, respectively.

If F is a contraction map, Banach's Fixed Point Theorem [64] guarantees the existence and uniqueness of the system of equations (3) and (4). This suggests iteratively updating the following equation:

$H! = F(H!!!, X)$ (5)

where $H!$ is the t-th iteration of H, and $H!$can be initialized randomly.

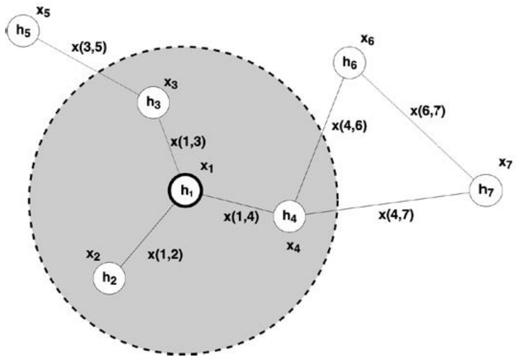


Figure 2 shows the intuition behind equations (1) and (5): to learn a node representation by propagating information from its neighbors, iteratively, until convergence.

$h!$ = ($x!$, $x(!,!)$, $x(!,!)$, $x(!,!)$, $h!$, $h!$, $h!$, $x!$, $x!$, $x!$)

Figure 2: Example graph of how GraphNN propagates information from the states and features of the immediate neighborhood of a node.

To learn the functions f and g, GraphNN defines a loss function at the supervised nodes, and uses a gradient descent

scheme: iteratively updating $H!$ until a convergence criterion is reached; calculating the gradients of the loss with respect to the weights of f and g; and updating the weights.

Although it is a simple and powerful model, GraphNN has several limitations. Most importantly, it is computationally inefficient to compute the iterations for the fixed point and requiring F to be a contraction map limits the modeling capacity of the approach, including the long range dependencies of nodes (see appendix A of [47]).

The Gated Graph Neural Network (GatedGNN) [47] is another recurrent graph neural network, and it improves on some of the drawbacks of GraphNN. This model modifies the original GraphNN substituting the recurrence function in equation (1) for a Gated Recurrent Unit (GRU) [65]. GatedGNN uses backpropagation through time (BPTT), unrolling the recurrence for a fixed number of T steps. While for a large graph this can present a drawback by requiring a large amount of memory to store the intermediate states computed over all nodes, on the other hand this removes the requirement for a contraction map in order to guarantee convergence. The model recurrence is defined as follows

$a!! = A!:[h!!!!. . . h!!!!] + b, \quad g!! = tanh(Wa!! + U(h!!!! \odot h!!!!),$

$z!! = \sigma(W!a!! + U!h!!!!), \qquad h!! = (1 - z!!) \odot h!!!! + (z!! \odot g!!), \qquad (6)$

$r!! = \sigma(W!a!! + U!h!!!!),$

where A is the modified adjacency matrix composed of two submatrices, one for outgoing edges, the other for incoming edges. Figure 3 shows the parameter tying and sparsity structure in the adjacency matrix, as well as an example of the unrolling of the recurrence for one time step. $\boldsymbol{Av}$: corresponds to the two columns of the submatrices $\boldsymbol{A}(\boldsymbol{out})$and $\boldsymbol{A}(\boldsymbol{out})$ referring to node v, and $\boldsymbol{z}$ and $\boldsymbol{r}$ correspond to the update and reset gates of the GRU.

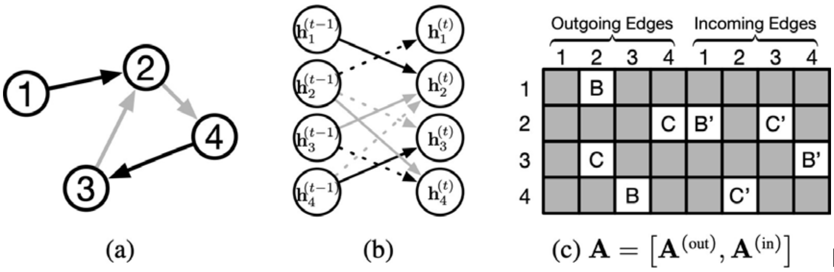


Figure 3: (a) Example graph, where edge color denotes edge type. (b) Unrolling of one time step. (c) Parameter tying and sparsity in adjacency matrix. Letters denote edge types. B′ corresponds to the reverse edge of type B. B and B ′ denote distinct parameters [47]. Reprinted with permission.

Other recurrent graph neural networks have been developed, including the Graph Echo State Network [66], Graphrnn

[50] and Stochastic Steady-state Embedding [49].

Convolutional graph neural networks

The generalization of the very successful CNN to non-Euclidean data such as graphs and manifolds has followed two distinct avenues, the so-called spectral methods and spatial methods. Briefly, spectral based methods define the convolution based on the graph Laplacian and use the corresponding Fourier basis in the spectral domain, and spatial methods use a localized parameter-sharing filter on the neighbors of each node, in essence, aggregating local features.

Spectral Convolutional Neural Networks (SpectralCNN) [51] was the first model to introduce the convolution for graph data. Given an undirected graph its normalized graph Laplacian is defined as

$L = I! - D!!/!AD!!/!,$ (7)

where $\boldsymbol{A}$ is the adjacency matrix and D is the diagonal matrix of node degrees. The graph Laplacian is a real symmetric positive semidefinite matrix which implies that it can be factorized as

$L = U\Lambda U!,$ (8)

where Λ is the diagonal matrix of eigenvalues - the spectrum - and $\boldsymbol{U}$ is the matrix of eigenvectors. Given a graph signal

$x \in R!$where $x!$ is the feature of the i-th node. The graph Fourier transform $\mathcal{F}$ - and its inverse $\mathcal{F}!!$ are defined by

$\mathcal{F}(x) = U!x = x,$ (9)

$\mathcal{F}!!(x) = U!x.$ (10)

The graph convolution operation of a graph signal x with a filter g on a graph G is defined as

$x * g = \mathcal{F}!!(x)(\mathcal{F}(x) \odot \mathcal{F}(x)),$

$= U(U!x \odot U!g)$ (11)

where $\odot$ is the Hadamard product. The equation above can be simplified, by considering a filter $g =$

$diag(\theta)$parametrized by $\theta \in R!$ in the Fourier domain, to the following expression

$x * g = UgU!x,$ (12)

where filter g can be understood as a function of eigenvalues of the Laplacian, that is $g(\Lambda)$.

This model has several drawbacks. It is computacional inefficient since multiplication by U is $O(n!)$ and calculating the eigen-decomposition is $O(n!)$. In addition, the dimensionality of the trainable filter depends on the number of nodes of the graph, and the filters are non-localized depending on the graph structure - if a graph changes at all, so will its eigenvalues and eigenvectors.

Chebyshev Spectral Convolutional Neural Networks (ChebNet) [40] proposes to approximate the filter by Chebyshev polynomials of the diagonal matrix of eigenvalues, that is,

$$h_!^{\,!} = \sigma\Big(\sum_{! \in \{!(!) \cup !\}} \alpha_{!''} W^{!!!} h_!^{\,!!!}\Big),$$

where $L* = 2L/\lambda!"\# - I!$ and $\lambda!"\#$ is the maximum eigenvalue. The Chebyshev polynomials are defined by the recursion $T!(x) = 2xT!!!(x) - T!!!(x)$ with $T!(x) = 1$ and $T!(x) = x$. In this setting, the computational complexity reduces to $O(KM)$ where K is the polynomial order of the expansion above and M is the number of edges, rendering the model linear with respect to the graph size. This also renders the filters spatially localized, since for an expansion of degree K each node only receives information from a node at maximum K hops away.

Graph Convolutional Networks (GCN) [37] extends ChebNet by limiting the Chebyshev expansion to only the first order, $K = 1$, and employing some additional modifications. It assumes $\lambda!"\# = 2$, simplifying equation (13) to

$x * g = \theta!x - \theta!D!!/!AD!!/!x.$ (14)

Setting $\theta! = -\theta!$and substituting $A$for $A* = A + I!$, equation (12) can be written as

$x * g = \theta(I! + D*!!/!A*D*!!/!x.$ (15)

Generalizing to the signal to C input channels and F filters for feature maps, the graph convolution can be written as

$Z = D*!!/!A*D*!!/!\Theta,$ (16)

where $Z \in R!\times!$, and $\Theta \in R!\times!$ is a matrix of filter parameters.

ChebNet and GCN bridge the gap between spectral- and spatial based methods. Equation (16) can be expressed as

$\sum$(16)

$h! = f(($

!∈{!(!)∪!)

$A!,!x!)\Theta),$

which can be interpreted as a spatial-based method, each node aggregating information from its neighbors.

$\sum$ Neural Fingerprints (Neural FPs) [53] generalized GNNs by using different learning parameters for nodes with different degrees, as follows:

$x = h!!!! +$

!!!

$h!!!!\theta!T!(\Lambda*))U!x,$

(17)

h!! = σ(xW!|!(!)|), (18)

where W! !(!) is the weight matrix for nodes of degree N at layer t.

Another interesting model is the dual graph convolutional network (DGCN) [67] which jointly uses two convolutions: one based on the adjacency matrix is the same as equation (16), and the second one is based on a diffusion process to capture global relationships by substituting the adjacency matrix $\boldsymbol{A}$ with the positive pointwise mutual information (PPMI) matrix [52].

Graph Attention Networks

Attention mechanisms [68], [69] are a recent development in deep learning that has had success in tasks such as machine translation. Figure 4 illustrates the intuition of why attention mechanisms could be helpful in modelling the neighborhood of a node, namely by leveraging the type of each neighbor to assign different importance weights.

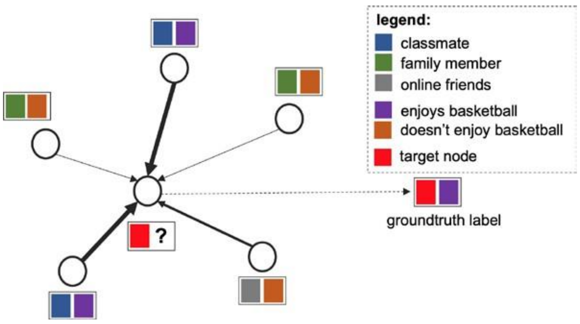


Figure 4: The type of each neighbor is used to assign attention, and the link size denotes how much attention to apply to each neighbor. This example illustrates how concentrating our attention on the node's classmates, would improve our prediction of the enjoyment of the activity [70]. Reprinted with permission.

Graph Attention Networks (GAT) [54] was the first model to incorporate an attention mechanism in GNNs by removing the requirement that all the neighbors of a node contribute with equal or pre-defined weights. Rather, the relative weights between two connected weights are learned as follows:

h!! = σ(

$\sum$

!∈{!(!)∪!}

α!"W!!!h!!!!),

(19)

where α!" is the attention coefficient of node j to i defined as

α!" = $softmax(g(a$![W!!!h!||W!!!h!])), (20) where a is a vector of learnable parameters and g is a LeakyReLU unit.

GAT also proposes incorporating a multi-head attention mechanism [69], and have the important advantage of being efficient since the computation of the node-neighbor pairs is parallelizable and because it can naturally be applied to nodes with a different number of neighbors.

Gated Attention Network (GAAN) [55] is an extension of GAT which, in addition to the multi-head attention mechanism, also incorporates a self-attention mechanism which replaces the averaging operation of GAT with an attention score on each attention head. For more details and different taxonomies of attention models in graphs, we refer the reader to a comprehensive review [70].

Graph Autoencoders

Graph neural networks have also been used in unsupervised learning settings. In particular, successful deep learning models such as autoencoders [71] and variational autoencoders [72] have been generalized to handle graph data. These models are usually developed to either learn network embeddings, such as Structural Deep Network Embedding [56] and Variational Graph Autoencoder [57], or to generate new graphs such Deep Generative Model of Graphs [58] and Graph Variational Autoencoder [59].

Some models have also incorporated adversarial training, in particular Generative Adversarial Networks (GAN) [73]. In a GAN, two networks compete against each other: the generator network is optimized to produce realistic samples of data that the discriminator network tries to distinguish from real data. GANs have been used together with GCN for generation of molecular graphs [60], link prediction, node clustering, and graph visualization [61].

Frameworks

In addition to the different types of GNN models that have been developed so far, some of which we describe above, there has been an effort to unify GNNs under a general and common framework. Non-local Neural Networks (NLNN)

[74] unifies different self-attention mechanisms, and Message Passing Neural Networks (MPNN) [75] generalizes several GNN approaches using a message passing scheme. In MPNNs, messages m!! at timestep t are passed from each node v as follows:

m!!!! =

$\sum$

!∈!(!)

M!(h!!, h!!, e!"),

(21)

$h!!!! \ = U!(h!!, m!!!!),$ (22)

where $U!$ is the vertex update function, $M!$ is the message function and $e!”$represents the features of the edge from node

v to u.

The Graph Networks (GN) model [41] generalizes both the NLNN and MPNN frameworks and other types of GNNs. It defines a GN block containing three update functions and three aggregation functions as follows:

$e!' \ = \ \varphi!(e!, h!”, h!”, u),$ $e!*' = \rho!\to!(E!'),$

$h!' = \varphi!(e!*', h!, u),$ $e*' = \rho!\to!(E'),$ (23)

$u' = \varphi!(e*', h*', u),$ $h*' \ = \rho!\to!(H'),$ where $\rho()$ are the message passing functions and $\varphi()$ the update functions.

Software

The research and application of GNNs has been greatly enhanced by the development and publishing of several open- source libraries, specifically written to handle GNNs. These are built on top of already powerful deep learning frameworks, such as PyTorch [76] and Tensorflow [77]. These GNN libraries can greatly reduce the time of testing and deployment of new models, by providing useful abstractions that simplify the code required while automatically handling several low-level optimizations, such as scaling, parallelization and taking advantage of sparse structure. It is also common for authors to release implementations of their models in these libraries, which are, in turn, often integrated in these libraries in a ready-to-use manner.

Library	**Reference**	**DL Framework**	**URL**
DGL	]78[	MXNet, Pytorch	https://github.com/dmlc/dgl
Euler	]79[	Tensorflow	https://github.com/alibaba/euler
Graph Nets	]41[	Tensorflow	https://github.com/deepmind/graph_nets
PyTorch Geometric	]80[	Pytorch	https://github.com/rusty1s/pytorch_geometric

Table 2: Graph deep learning libraries.

Graph neural networks for traffic forecasting

The connection between graphs and roads or maps is as old as graph theory, dating back to Euler's formulation and solution to the Königsberg problem. Nodes can represent road intersections and edges can model the road segments between them. Or, almost as naturally, nodes can represent points on a road segment where a traffic variable is being measured by a sensor and edges represent some relationship between these locations, such as the shortest path distance between them. The addition of a temporal component can be just as natural, as Figure 6 illustrates. Typically, each node in a graph would define a time-series of a feature vector, such as the history of traffic speed and traffic flow at a certain location.

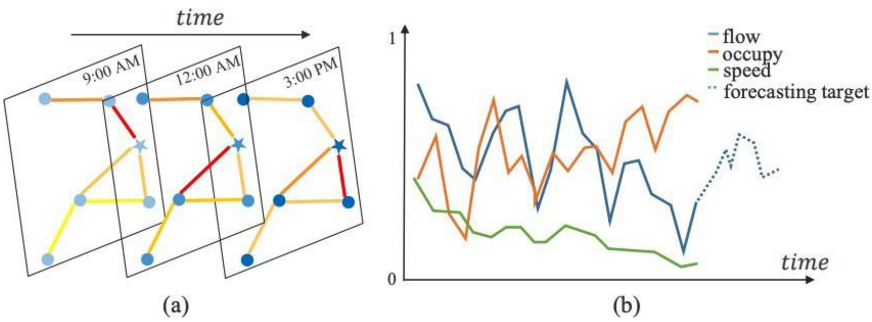


Figure 6: (a) Typical spatio-temporal structure of traffic data with each time slice forming a graph. (b) Representation of a three-dimensional time series at a certain node and a forecast of one of these features. [8]. Reprinted with permission.

Traffic forecasting based on graph neural networks can be viewed as the problem of extending the models of the previous section and the categories of Table 1 to the temporal domain. In principle, combining the many types of GNNs approaches with the immense diversity of existing time series analysis models and forecasting methods offers a wide space of possibilities.

In this section, we will present and compare the graph neural network models for traffic forecasting that have been developed so far. These have in common a graph neural network as a centerpiece of the model and they vary along most modern deep learning paradigms, combining recent techniques that have been found powerful in other domains of applications. These include attention mechanisms [8], [55], multi-graphs [81], dynamic graphs [82], diffusion kernels [83], graph wavenet [84], inception models [85], deep graph infomax [86], residual nets [87], wavelet transforms [88], among others [6], [7], [89]–[95]. In section 4.1. we review these models and compare different approaches, and in Section 2 we describe typical datasets in which these models are evaluated.

Models

Table 3 lists the GNNs models developed for traffic forecasting so far, which we describe below. We start by describing Spatio-Temporal Graph Convolutional Networks (STGCN) [92] and Diffusion Convolutional Recurrent Neural Networks (DCRNN) [83]. As of the writing of this review, these two models stand out as the most cited and most often compared to when developing a new model, in part because they are some of the models first developed while also representing opposite approaches in some aspects.

STGCNs combine the spectral-based ChebNets [40] with 1D-CNNs to model and predict traffic speed at various locations where sensors are located. The GCN and the CNN operate alternately along several layers, with the GCN capturing the spatial dependency while the CNN captures the temporal dependency. Figure 7 shows an illustration of scheme similar to the one used by STGCN, in which a CNN is combined with a GCN.

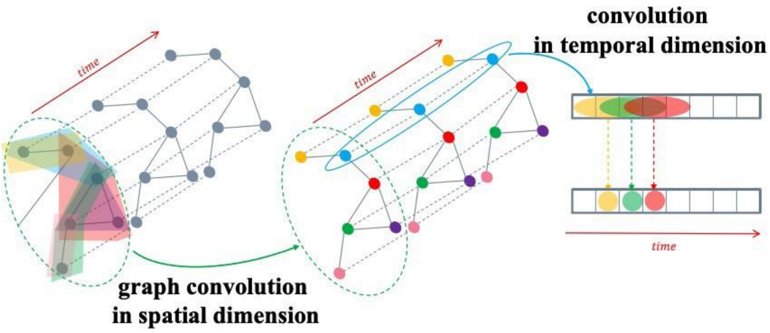


Figure 7: Illustration of how to combine GNN and CNN to capture the spatial and temporal dependencies, respectively [8]. Reprinted with permission.

DCRNNs take the opposite direction: they use RNNs instead of 1D-CNN to model the time dependencies and, in addition, use a spatial-based GCN for the spatial dependency instead of a spectral-based one. This is done by incorporating the GCN inside a GRU. Based on Diffusion-Convolution Neural Networks [96], DCRNN uses the probability transition matrix $P = D!!A$ to define the graph convolution as follows:

$H =$

!

$\sum$

!!!

$f(P!XW(!))$,

(24)

where $f()$ is an activation function and $W(!) \in R!\times!$. Effectively, DCRNN assumes that by passing information from node to node the network can reach an equilibrium state which is captured by the probability transition matrix. DCRNN also uses an enconder-decoder architecture to predict future timesteps.

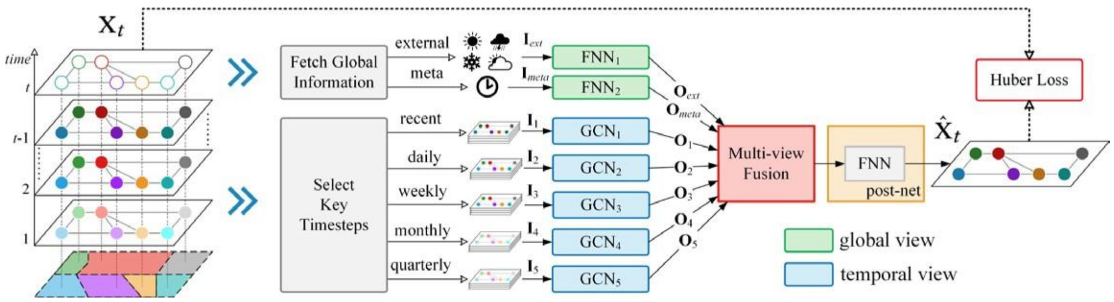
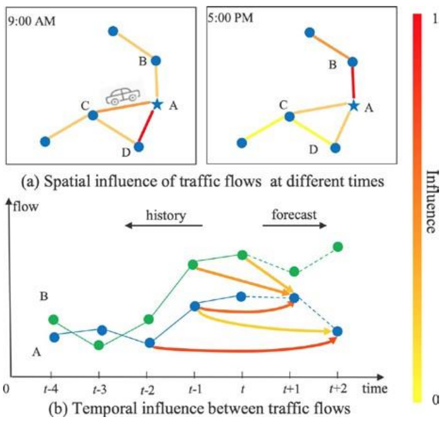


Figure 8: Architecture of MVGCN, displaying the views capturing different timescale dependencies, and their fusion in the final layer. [90]

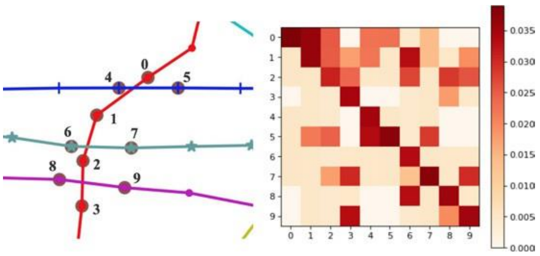
A different and promising approach has been proposed by several recent models, including Multi-View Graph Convolutional Networks (MVGCN) [90], Multi Residual Recurrent Graph Neural Networks (MRes-RGNN) [87], Motif-based Graph Convolutional Recurrent Neural Network (Motif-GCRNN) [88] and Spatial-Temporal Graph Inception Residual Networks (STGI-ResNet) [85]. In these approaches, typical repeating time patterns are grouped in order to leverage the inductive bias we know is present in typical traffic, such as daily or weekly periods. As an illustration, if one is predicting traffic speed at 9am on a friday, in principle, one can make a better prediction by considering not only the last previous hours, but also, for example, the traffic at 9am in the previous four days of the week, and in the previous fridays, at 9am. These different views are then fused in the last layers of the architecture. This fusion layer is also learnable. Figure 8 shows the architecture of MVGCN which exemplifies this approach. As shown in the figure, these approaches can also typically handle exogenous factors such as weather and irregular events (e.g., road accidents), that have a significant impact in urban traffic.

Model	.Ref	Scope	Predicts	Data source	Datasets	?Open dataset	Code avail-?able
ST-GCN	]92[	Fw, Ur	S	L	BJER4, PeMS	✓ ,✗	✓
DCRNN	]83[	Fw	S	L	METR-LA, PeMS	✓	✓
MRes-RGNN	]87[	Fw	S	L	METR-LA, PeMS	✓	✗
TGC-LSTM	]7[	Fw, Ur	S	L, FCD	LOOP, INRIX	✓ ,✗	✗
ASTGCN	]8[	Fw	F, S	L	PeMSD4, PeMSD8	✓	✓
STDGI	]86[	Fw	S	L	METR-LA	✓	✓
MVGCN	]90[	Ur	F	FCD	TaxiNYC, Tax-iBJ, BikeDC, BikeNYC	✓	✗
DST-GCNN	]82[	Fw, Ur	S, V	L, FCD	METR-LA, TaxiBJ	✓	✗
GSRNN	]91[	Ur	F	FCD	BikeNYC, TaxiBJ	✓	✗
Graph Wavenet	]84[	Fw	S	L	METR-LA, PeMS	✓	✓
3D-TGCN	]6[	Fw	S	L	PeMS	✓	✗
ST-UNet	]93[	Fw	S	L	METR-LA, PeMS	✓	✗
GaAN	]55[	Fw	S	L	METR-LA	✓	✗
Mo-tif-GCRNN	]88[	Ur	S	FCD	TaxiChengdu	✗	✗
STGi-Res-Net	]85[	Ur	F	FCD	Didi Chengdu	✓	✗
T-GCN	]94[	Fw, Ur	S	FCD	SZ-taxi, Los-loop	✓ ,✗	✗
FlowConv-GRU	]97[	Ur	F	FCD	TaxiNYC, TaxiCD	✓	✗

Table 3: Graph Neural Networks approaches to traffic forecasting. For each publication, we list the scope of application (Ur: urban, Fw: freeway) , the variables predicted (S: speed, F: flow, V: volume), the data source (L: loop counters, FCD: floating car data), the datasets used for experiments, whether or not these datasets are open, and whether there exists open-source code implementations of the models.



Attention mechanisms have also shown to be a promisingapproach to spatio-temporal forecasting. In addition to the GaAN architecture [55] described in Section 3.1.3, Attention Based Spatial-Temporal Graph Convolutional Networks (ASTGCN) [8] combine attention mechanisms on both the spatial and the temporal components with a multi-view approach on temporal patterns (namely, recent, daily-periodic and weekly-periodic). Figure 9 illustrates the intuition on how attention mechanisms can help make better predictions as well as output more interpretable models.



(c) Attention matrix obtained from the spatial attention mechanism.

Figure 9: (a) and (b) Spatial-temporal correlation diagram of traffic flow. (c) Attention matrix of sub-graph with 10 detectors, where the i-th row indicates how strong the time series of node i correlates with every other node. As an example of the interpretability aspect of this model, we can see that it indicates that pairs of nodes most strongly correlated tend to be spatially close, such as 1 and 6, 5 and 4, and 9 and 3. [8] Reprinted with permission.

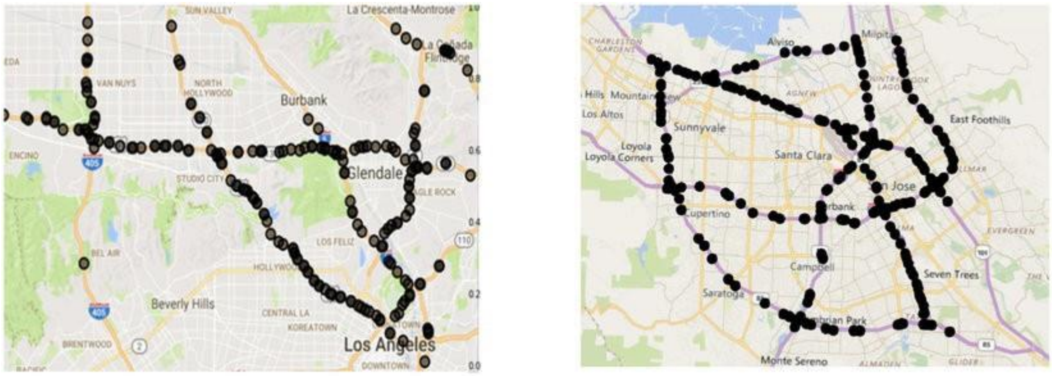
Another rich approach has been to enable models to learn the graph adjacency matrix from the data and its patterns such as time series similarity between different nodes instead, or in addition to, the usual spatial distance. Variants of this approach are proposed by models that include Dynamic Spatio-Temporal Graph-based CNNs (DST-GCNN) [82], 3D Temporal Graph Convolutional Networks (3D-TGCN) [6], Graph WaveNet [84] and FlowConvGRU [97].

Finally, other models focus on leveraging other approaches such as the sparsity of traffic data [91], pooling and unpooling layers [93] or unsupervised learning of node representations [86].

Datasets

In spite of the differences described above, nearly every model has been experimentally evaluated in similar datasets with a similar configuration. In particular, the timestep of the datasets is, with few exceptions, 5 minutes, and the prediction horizon is 15, 30 and 60 minutes (that is, 3, 6, and 10 timesteps). The extension of the dataset is also very often around 4 months, which is equivalent to about 35000 timesteps.

Two datasets in particular standout as the most used for benchmarking: METR-LA and PEMS-BAY. These datasets contain traffic information collected from loop sensors at various locations of two networks of freeways in California, one in Los Angeles, the other in the Bay Area. Typically only a small fraction of the data is used. For example, data is aggregated in 5 minutes interval and only between 200 and 1000 sensors are used to test the models.



(a) METR-LA (b) PEMS-BAY

Figure 6: Sensor distribution of the METR-LA and PEMS-BAY datasets [83]. Reprinted with permission.

Challenges and research opportunities

While the results obtained in various traffic forecasting tasks by deep learning models and, notably, graph neural networks have been very successful, there are still a number of open issues and traffic forecasting is still an unsolved problem. These challenges constitute a rich set of research and engineering opportunities [3], [98] which include integrating in a systematic way exogenous factors (such as road accidents and weather), designing more sophisticated evaluation metrics, integrating traffic forecasting with other downstream applications, going from volume or speed prediction to travel time prediction, improving the interpretability of the models and moving from prediction to causation. Additionally, ongoing work tackles the problem of developing Bayesian methods that provide adequate predictions beyond point estimates (such as confidence intervals) and tackling the issue of data ageing and concept drift by developing models that take into account when road segments or bus lines are added or removed from the network.

Acknowledgments

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Building Maintenance Modelling and Planning

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Abstract

Building maintenance is an essential activity needed to maintain assets at a certain operational level that is determined by their purpose and use. The building maintenance activities are cumbersome in terms of determining their contents and timing of application. Critical activities can be highly expensive and if not undertaken in time can have catastrophic consequences. In fact building maintenance costs exceed the initial costs of building construction significantly. This paper presents and examines the area of building maintenance research with particular reference to modelling and optimisation. The paper covers the history and importance, social and economical, of building maintenance and discusses the current research in maintenance modelling to support decision making. The building maintenance management approaches presented in literature are also reviewed covering the current application software tools used and those emerging with promising potential including Building Information Modelling (BIM). The paper is concluded with a proposed building maintenance framework discussing the typical stages of maintenance planning cycle .

Key words: Building maintenance, Building Information Model (BIM), Condition Based Maintenance, Maintenance concept.

1 Introduction

Building maintenance is essential to maintain buildings' functionality and it is acknowledged as an important area that is worthy of study. It is broadly appreciated that the cost of maintenance of a building over its life can be much higher than its initial construction cost. Evans et al [1] study of the long term costs of owing and using buildings suggested a ratio of 1:5:200 relating the initial cost of the building to that of maintenance and operations respectively. Whether this ratio exaggerates the maintenance cost that can be open for debate, but maintenance cost over the life of the asset depends on the type of building and its use.

Wood [2] presents brief introduction to the recent history of building maintenance in the UK. He discusses the public policy with regard to building construction and maintenance from the focus on reconstruction following WWII, the slum clearance, introduction of building regulations, the modernisation of slums to the privatisation of council houses and the introduction of the Private Finance Initiative (PFI) and the Public/ Private Partnerships to organise involvement of the private sector in the public sector construction work that was previously carried out by councils.

The first aim of this paper is to review the building maintenance management approaches presented in literature. The paper then explores how can Building Information Modelling (BIM) be used to support building. The paper is concluded with a proposed building maintenance framework.

2 Building Maintenance Management Approaches and Techniques

Interest in research in building maintenance management and planning started to strengthen in the 1960s. Lee [3] published a book on Building Maintenance Management in 1976 which demonstrated the complexity of this area and its social and economical importance. He further stressed the importance of using management techniques in this area. He showed the consequences of delaying maintenance and the importance of inspection, scheduling and the planned/ preventive maintenance. Later in 1979 Gibson[4] edited book on Developments in Building Maintenance-1. This book demonstrates the significant achievement of building maintenance research and the emerging topics that remain of current research interest to date particularly the use of decisions models. Jardine [5] later developed these modelling approaches to optimise maintenance activities which set the foundation of modern maintenance modelling and optimisation.

There is a variety of approaches and techniques published in literature for planning, scheduling and budgeting building maintenance. The most notable of these approaches are discussed below:

2.1 Reliability Analysis

Wu et al[6] argue the use of reliability analysis can lead to improved building performance over its whole life. The Life Cycle Costs (LCC) typically show a drop followed by rise with the increase of reliability. This is explained by increasing construction cost and reducing maintenance cost with increasing the reliability level target. Hence there is need to carefully select the maintenance policy including the frequency of interventions in order to minimise the LCC. Wu et al[6] analysed the impact of reliability on each stage of the whole life cycle of the building system including: client requirements and briefing, design, installation, operations and maintenance and disposal/ reusing and recycling. Reliability analysis based on data collection can help in re-developing or updating the maintenance policies in order to adapt to practical use/ operating environment through optimising life cycle costs and or performance.

2.2 Reliability Centred Maintenance (RCM)

RCM is a maintenance planning approach that was first developed in aircraft industry. Although the formal definition of RCM is that it is an approach for identifying effective and efficient preventive maintenance tasks and intervals according to specific procedure(IEC 1999 [7]), Rausand and Vatn [8] noted that applying RCM can include identification of repair upon failure policies, inventory management of parts optimisation and logistic consideration. Rausand and Vatn [8] identify 12 steps for RCM analysis process ranging from functional failure analysis, critical item selection and failure modes effects and criticality analysis (FMECA) to selection of maintenance action and determination of maintenance intervals.

El-Haram and Horner[9] provide one of few applications of RCM in building maintenance. The objectives of their study was to apply integrated logistics support to the development of cost effective maintenance strategies for existing building stock using RCM approach tailored for application to construction projects. A pilot study was undertaken on 18 residential properties. The study details the four steps used including: carrying out building condition survey, apply FMEA and RCM, evaluate the maintenance costs and comparing the results of the condition survey with RCM. The condition survey identified 4 building elements where 74% of failures occurred. They also identified the causes of failures. Following the application of FMEA to identify all possible ways of each element failure with the causes and effects of these failures RCM was applied to identify the cost effective maintenance tasks and their consequences. The pilot study shows that the potential benefit of applying RCM is a reduction of maintenance cost by 18.5% in addition to other benefits including higher levels of health and safety, help in establishing maintenance programmes and in preparing maintenance budget.

2.3 Key Performance Indicators

The huge spending on maintenance, estimated at 1500 billion Euros in Europe[10], has motivated senior managers and maintenance engineers to measure the contribution of maintenance towards total business goals [11]. Maintenance Performance Indicators (MPIs) are the means to measure the performance of a maintenance process, are ratio of two maintenance related variables and can act as early warning system for maintenance process indicating the present status of the process in order to make prediction and take corrective action [11].

2.4 Condition Based Maintenance

Condition based maintenance policies have advantages over the classic and simpler to apply age based maintenance policies. In a typical age based maintenance an optimal maintenance interval is estimated using variety of mathematical models that are based on assumption of quality of maintenance action e.g. renewal, minimal repair etc. In condition based maintenance, system condition is monitored and maintenance interventions are undertaken whenever the condition drops below certain critical level set by the manager or when a failure occurs. Condition monitoring can either be continuous or carried out at every preset interval of time. Monitoring can be carried out by operators “inspection” or through the use of special equipment that can alert the user to the drop of performance.

There are few publications on the application of condition monitoring in building maintenance. Straub [12] presents a condition based approach using six-point condition scale. Different types of performance loss are identified e.g. technical performance and fire and social safety with each linked to specific maintenance actions. The condition assessment method adapted involves visual inspection followed by deciding the type, intensity and extent of defects. This approach allows building inspectors to provide facility managers with objective data about performance loss and defects in building components. A drawback of the condition assessment approach is the amount of data which should be updated continuously.

Alani et al[13] established from questionnaire responses from 100 companies involved in maintenance and facilities management work that 95% of all organisations used condition based maintenance assessment methods for the prioritisation of maintenance operations. They also undertake a comparative study of 4 methods used to set priorities for building maintenance elements and the results show a good level of agreement on setting priorities for building maintenance at levels 1 and 2 which indicate that the elements which require immediate attention and repair work have been identified. However there were disagreements on identifying priority 3 elements which require long term maintenance.

In a more recent study by Hegazy et al[14] the authors attempt to circumvent inspection problems of subjectivity and the high cost and time required by using reactive-maintenance data to develop indicators for the condition of building components. The study used data for 88 schools and identified 23 building systems. They established a relationship between the condition of a component and the reactive maintenance performed for that component per year showing that the more the reactive maintenance performed the poorer the condition of the component. The authors also presented methods for establishing the condition threshold at which maintenance interventions are introduced.

2.5 Operational Research (OR) Models

Several approaches for building maintenance originated in the field of OR. These include delay time analysis, Markov models and simulation.

Inspection plays a central role in building maintenance. The pioneering work of Christer[15] on delay time modelling had an early application in the area of using inspection in building maintenance. The concept of this approach is that there is a “delay” time elapses between origination of a fault and first detecting it. By studying the distribution of this delay time it is possible to identify the best inspection policy including inspection interval. Christer [15] argues the importance of inspection policies in building maintenance. Since the publication of this paper this area of delay time modelling has expanded and many studies were carried out on estimating this distribution. One of the few applications in building maintenance is the study of Redmond et al [16] on modelling the deterioration and maintenance of concrete structures. A three phase delay time model that covers the cracking and spalling in concrete was developed and models were formulated to predict the cost effects of maintenance and inspection decision options.

Another OR modelling approach used in building maintenance is the use of Markov decision models. There are many variations for Markov models but they all assume the Markov property that the state of a system or process does not depend on its previous state i.e. that the system has no memory. This simplifying assumption has many applications in modelling. Winden and Dekker[17] presents model for using Markov decision process in modelling the maintenance of four building elements, viz. masonry, pointing, window frames and painting. The model can determine the maintenance policy that ensures a specific average quality level at minimal cost.

Al-Zubaidi and Christer[18] uses simulation to model building maintenance manpower for hospital complex in order to investigate the potential gain from using different manpower management and operational procedure. The model can simulate various situations accounting for daily variation in maintenance demand, sickness and holidays and the characteristics of different trades.

2.6 Innovative practices

Wood [2] refers to his research findings in identifying a number of innovative practices in building maintenance. These include: JIT Maintenance by getting the maximum life from each building component, Intelligent Building Maintenance which involves identification of information from data and relating it to creation of comfortable building environment, Call Centred Maintenance to identify its key role in providing maintenance regime and Sustainable Building Maintenance leading to sustainability of buildings and operations. All these innovative approaches can represent best practice in building maintenance.

3 Maintenance and Building Information Modelling (BIM)

Building Information Models or BIM is a relatively recent approach which is essentially a digital representation of the physical and functional characteristics of a facility [19]. BIM covers all stages of a building from design and construction to operations and maintenance. The expansion in the use of BIM will lead to accumulation of maintenance data in BIM models which can support models that are used in effective building operations and maintenance. In a recent paper Ilter and Ergen[20] review the current status and research directions in the application of BIM for building refurbishment and maintenance. They identified 5 subtopics of current research interest including access to and integration of maintenance information and knowledge.

Shariff and Kobbacy [21] stress the importance to start understanding how BIM maintenance information will be used in maintenance management and indeed how the information in BIM can be used to project the maintenance requirements as early as the design phase. In other words the availability of this integrated system will lead to consideration of maintenance requirements at the design stage and hence maintenance cost will influence building design. Furthermore BIM will provide appreciation of maintenance requirements from the design stage. Large organisations now look primarily at facility performance rather than the physical structure [19]. For example the USA General Services Administration (GSA) has recently awarded contract to design, install and maintain major power facility. Guillen et al [22] presents an up to date study on asset management for building within the framework of building information modelling development.

4 Proposed Building Maintenance Framework

There are a number of approaches for maintenance planning in Literature including: Reliability Centred Maintenance, RCM [8], Waeyenbergh and Pintelon approach[23], Decision Making Grid (DMG) approach [24], Value- driven maintenance planning [25] and Marquez et al approach [26].

Here we propose a building maintenance framework in Figure (1) below followed by discussion of its various stages. In proposing this framework we consider an organisation which has responsibility for maintaining buildings or estates. Such organisation can be a company, council, hospital etc.

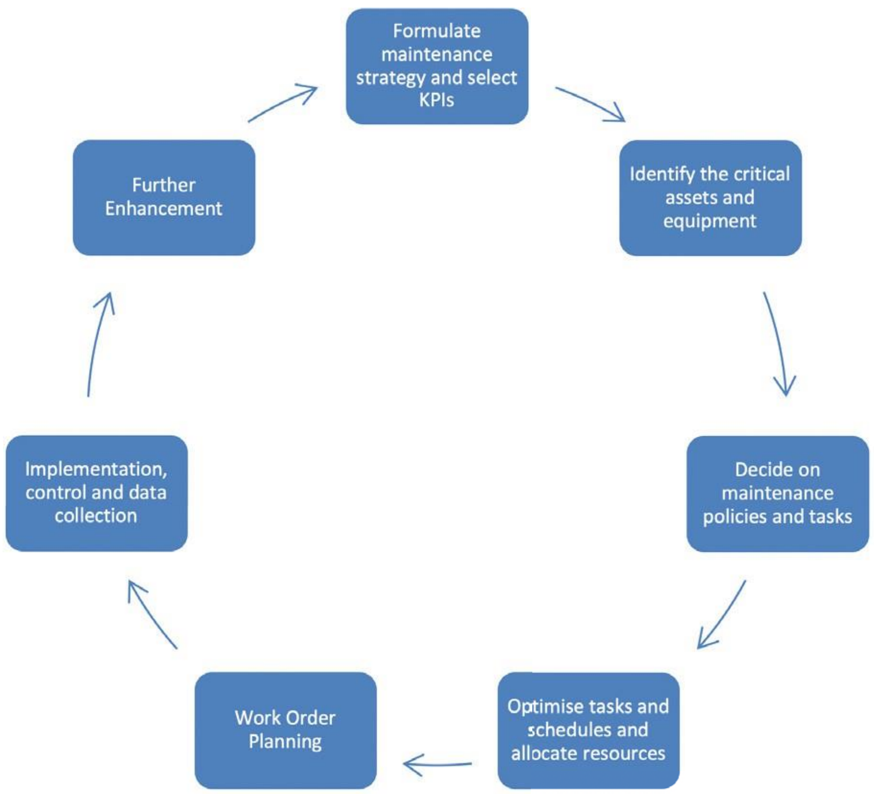

Figure (1) Building Maintenance framework

Formulate maintenance strategy and select KPIs

Maintenance strategy and objectives must be consistent and should support the organization strategy in achieving its objectives. Maintenance objectives can include one or combination of the following: maximise building/ equipment availability, minimise operations, maintenance cost or energy consumption, enhance building/ equipment performance and safety. Key Performance Indicators (KPIs) must be clearly identified and time linked target objectives must be stated and a statement about how they will be achieved. KPIs are measures of achieving maintenance goals and business objectives and can include: down time, building/equipment availability, preventive maintenance backlog and budget compliance.

Identify the critical assets and equipment

This can be rather complex process and there are different approaches to achieve it. In general the maintenance manager must decide on types and levels of risks for asset criticality analysis. Dimensions of risk assessment include: Quality, Reliability, Environment , Safety etc. There are many techniques that can be broadly divided into qualitative and quantitative [27]. Quantitative methods typically use the concept of Probability/ Risk Number PRN and the qualitative methods are used when no data are available.

Decide on maintenance policies and tasks

Various approaches can be used to decide on selection of maintenance policy e.g. Decision Making Grid (DMG) [24], Decision Tree [23] and RCM[8]. The DMG is an interesting approach that aims at answering the maintenance effectiveness questions i.e. which system or building element should we improve and how? There are two stages. The first is the decision making grid DMG which identifies the type of maintenance action based on failure history. Policies are allocated according to the location on the grid. For example if frequency and downtime are low you can use operate to failure and if downtime and frequency are high then use design out approach . The second stage is to use the Analytical Hierarchy Process (AHP) to priorities systems that needs attention.

Optimise tasks and schedules and allocate resources

Optimization of maintenance tasks and resource allocations are essential step in order to achieve efficiently maintenance leading to achieving maintenance objectives e.g. minimizing cost, maximizing availability. Models can vary from simple analytical models to decide on optimal spare parts ordering and stocking policies to complex simulation models that are used to schedule maintenance activities and allocate resources e.g. manpower, tools, etc.

Work Order Planning

This area is seldom discussed by academics though it is of great practical importance. It deals with the operational/ action planning and scheduling of maintenance activities. The book by Doc Palmer [28] on maintenance planning and scheduling views planning as “the preparatory work given to individual maintenance work orders before assigning them to specific craft persons for work execution”.

Implementation, control and data collection

Having planned for maintenance activities and assigned work orders to crew, implementation will proceed. Monitoring, recording and reporting of maintenance execution is essential to ensure achieving maintenance objectives. A precursor to monitoring and control of maintenance activities is the collection of appropriate data about the various aspects of maintenance. In modern organizations computerized maintenance management systems (CMMSs) are used.

Further enhancement

Further enhancement starts with Maintenance Performance Management (MPM). Utilization of emerging techniques and technology such as e-maintenance will enable continuous improvement. The use of life cycle analysis is particularly useful in understanding the different elements of asset costs over its entire life such as: planning; research & development; production; operation; maintenance and disposal. This particularly important for capital replacement decisions.

5 Conclusions

This paper is concerned with modelling and planning of building maintenance. We have identified in literature 6 main approaches that are used in building maintenance research. These were discussed and evaluated. The potential benefits from the current development and implementation of BIM on building maintenance have been outlined. We believe that over the coming few years with the implementation of BIM significant amount of maintenance data will be accumulated which will enhance building maintenance modelling and planning. The paper is concluded with presenting an outline design of building maintenance concept, which is a prerequisite for developing effective and efficient building maintenance.

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Big Data Based Maintenance, BDBM--The Main Trend of Smart Maintenance

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Abstract

We raised 12 different directions on smart maintenance, which including smart maintenance strategy generation. In current days , the data will play more and more important role in decision making for maintenance strategy.

In this paper, the author describes the concept of Big Data Based Maintenance, i.e. BDBM. The input data of the system is from four sources:

The process control system, DCS or PLC, such as temperature, speed, pressure, etc.;

The additive condition monitoring system, such as vibration, infrared monitoring result;

The inspecting discoveries from shop-floor operators;

The historical records of the equipment.

From above mentioned data and historical failure records, the system will find the feature values. Each value is given a trap range, while the current operation value falls into the trap, the system will issue an early-warning, and generate an accurate maintenance package, which includes 6W,2H and 1S, i.e., What · maintenance content, When, time point, Where, which equipment, Which, the component, the part of equipment, Who, the maintenance technician, Why, the reason, the evidence, How, the flow chart, tools, methodology of maintenance, How Much, the standard of maintenance, and Safety, the safety instruction of maintenance.

The system should self-leaning from the reality, and approach the accurate decision making inch by inch.

The authors begin to apply the system in subway transportation, power plant, and further practice should be continuing.

Anyway, the author predict that, BDBM will be the main trend of future smart maintenance.

KEYWORDS: Big data, Smart maintenance, Accurate maintenance

Introduction

Around 5 years ago, we raised 12 issues of smart maintenance, such as Intelligent inspection and monitoring, Intelligent lubrication, Intelligent information processing, Intelligent failure diagnosing, Intelligent spare part managing, Intelligent strategy generation, Intelligent knowledge managing, Intelligent repair instruction—IETM, Intelligent training, web safety intelligent managing, Intelligent MRO managing, as well as Maintenance Robot. Fig. 1 shows the 12 issues of smart maintenance.

Among maintenance strategy, the important trend should be " The Big Data Based Maintenance---BDBM". Not because we are in the Time of Big Data, just because of the technological development of equipment.

In some plant, many engineers reflect that, it is not easy to persuade the higher leader to invest condition monitoring instruments. However, some data in the control system such as DCS or PLC reflects the degradation indirectly, but not be used. Another useful data is the historical records related to maintenance, spare parts changing, and failures happened which will help to predict and relocate new failures; The third issue of data comes from the operator's daily inspection by human organs or PDA; If the aforementioned data are not enough to predict or locate the failure, then the last issue of data---condition monitoring measure should be introduced. Hence, the last and the most expensive method should be adapted under the Lean Environment.

Fig.1 12 issues of smart maintenance

Through data collection and integration, and failure diagnosis, the outcomes should be maintenance schedule, content and spare part changing information, which we call maintenance package. The general framework is shown by Fig. 2.

Fig. 2 The general framework of BDBM

The Category of BDBM

In fact, not all equipment is suitable for BDBM. If the consequence is not serious with small economic lost, zero accident, no environmental damage, no quality damage, no health affect and no obvious chain damage for the plant, then breakdown maintenance (BM) is the most economical strategy. If the plant or part of the equipment has an obvious exhausting interval, the regulation is handled by us, and other parts will run normally within this period, then time based maintenance (TBM) is the best strategy. There also be no available monitoring measure of the failure diagnosis for some equipment. So, BDBM is only suitable for the remaining equipment.

Before BDBM, the risk analysis is necessary to focus to the high risk area and plant. The main structure of risk analysis is shown by Fig. 3.

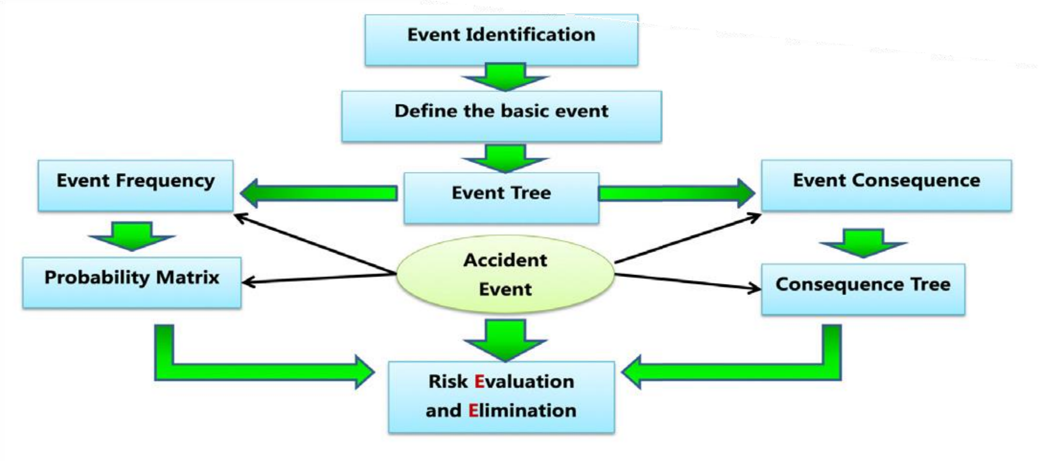

Fig. 3 The main structure of risk analysis

The Significant of risk analysis is as follows：

Let higher leader focus to High Risk Area or Equipment ；

Reinforce the investment to the high risk area or equipment;

BDBM will first choose the High Risk Area or System to test;

Risk is a dynamic concept, changing with different loading time, different age of the equipment. So, reviewing and drawing a Risk Map every half year is necessary.

The Logic Process of BDBM

The main logic of BDBM is as follows ·

Determine the high risk equipment ·

Extract the Feature Value according to different failure mode of equipment ;

Design the feature value trap threshold X-day, Y-day and Z-day before the breakdown occurs based on historical failure process ;

Monitoring the feature value continuously or with high frequency;

Lower than 50% Feature Values drop in the "trap", then a light warning start, and a predictive period is given;

Exact 50% Feature Values drop in the "trap", then a middle warning start, and a predictive period is given;

All Feature Values drop in the "trap", then a strong warning start, and a predictive period is given;

A maintenance decision is made and a maintenance package is generated.

Fig. 4 shows the main logic flow of BDBM.

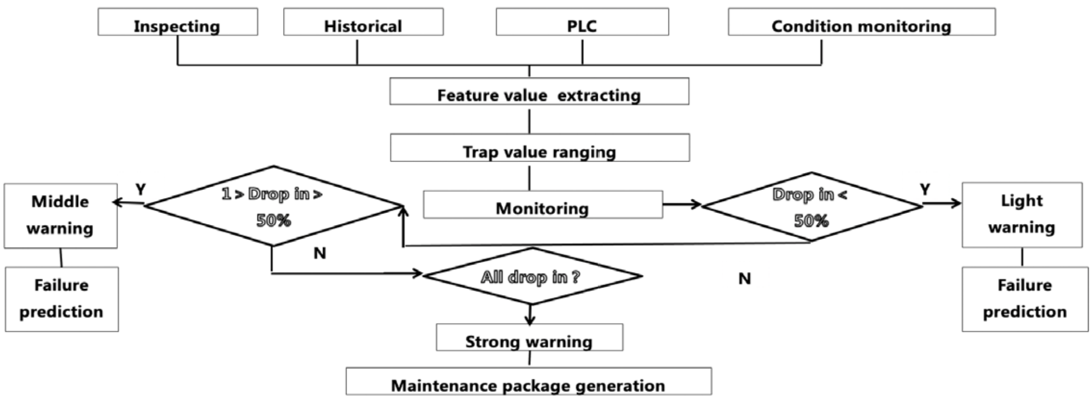

Fig. 4 the main logic flow of BDBM

5. BDBM---Case Simulation

We design 3 thresholds on the curve before 30, 15 and 7 days as traps to monitor the future status of equipment as is shown in Fig. 5. ·

During the process of monitoring, we discover"Flow"get into Tr30-1, then the light warning is started, and "the failure will happen within 30 days" is predicted. While 3 feature value all get into traps, then the strong warning is started, and "the failure will happen within 7 days", and the maintenance package is generated.

Just like the maintenance of aircraft, an accurate maintenance package should be generated as is shown in Fig. 6

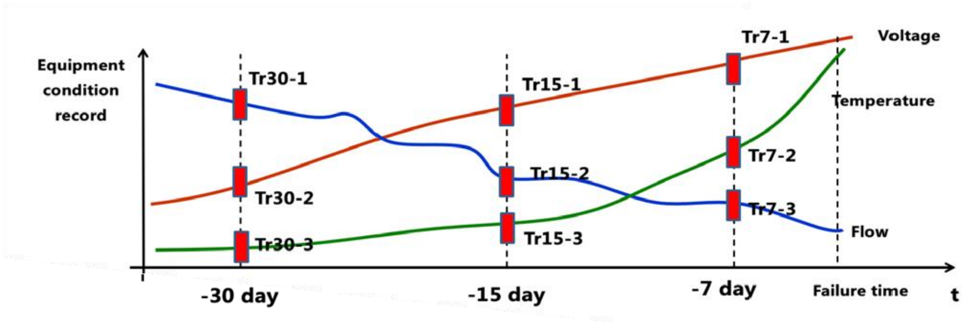

Fig. 5. The case simulation of feature value monitoring and trap threshold design

Concerning the outcomes of BDBM, three optional maintenance modes of dynamic maintenance package can be chosen according to the reality which is shown as Fig.7.

When we chose the restoration maintenance mode, although the performance will be restored, but the frequency of maintenance will not be reduced, may be increased because of the degradation of the equipment. When we chose part replace maintenance mode, the performance will be restored regularly, the frequency of maintenance should be keep a constant because of the function of new parts. When we chose the proactive or upgrading maintenance mode, then the performance should be increased and the frequency should be decreased too.

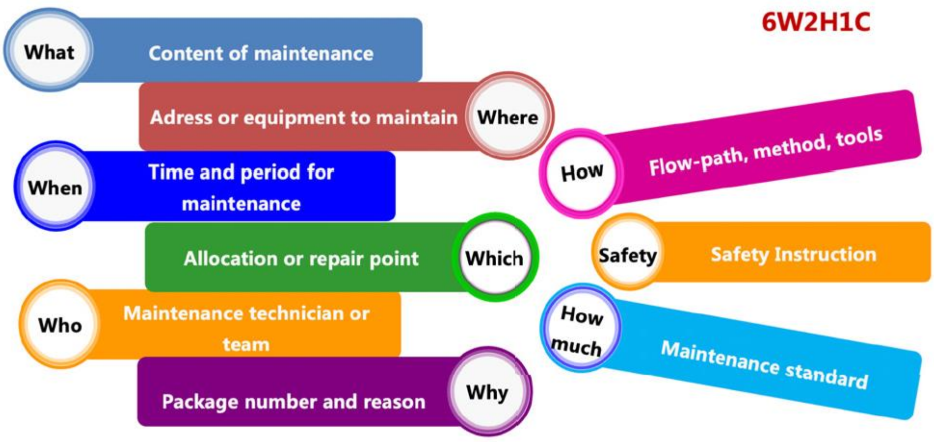

Fig. 6 Maintenance package generated with 6W, 2H and 1S

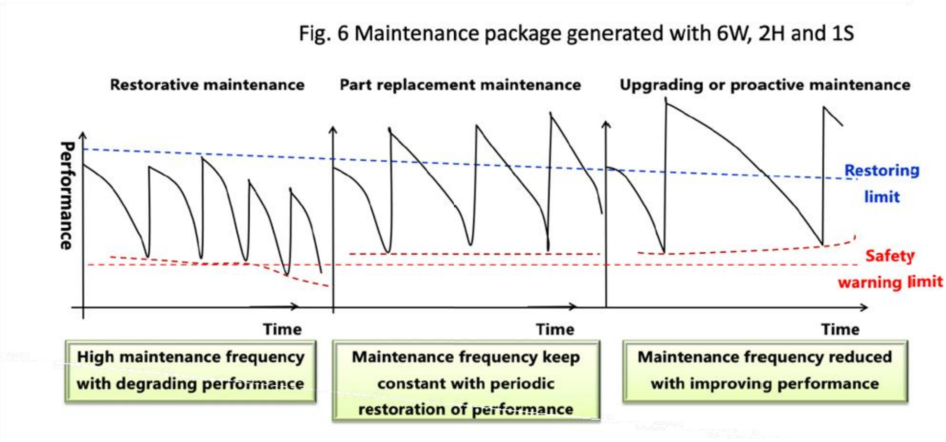

Fig.7 The different modes of maintenance and results

Self-learning is necessary to improve the BDBM continuously. The process of self-learning is shown as Fig. 8.

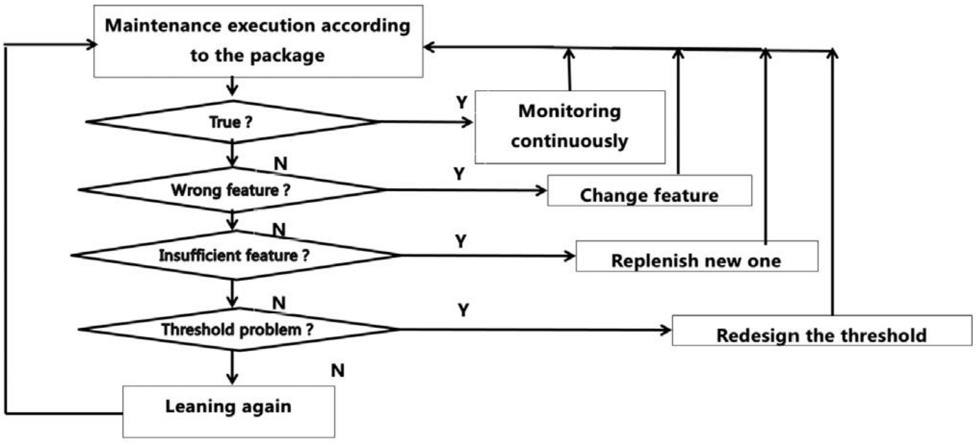

Fig. 8. process of self-learning

After the maintenance, if the reality prove that the prediction is correct, then the monitoring should be executed continuously. If the maintenance process discover that, the prediction is not correctly, then the feature we extract should be reviewed, we can change some new features to begin our new test. If the features we chose are not enough to reflect the failure, then we should add some new features to guarantee the prediction of failure. Some time the problem because of the range of trap threshold, then we can solve the problem by redesigning the threshold. Then go back to the beginning point again.

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Development of PMS for Road and Airport Networks

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Abstract

One of the main difficulties for an infrastructure manager is to achieve the most efficient way to apply his financial resources to maintain the network level of service. The use of a Pavement Management System (PMS) aid to decide about the set of interventions to be chronological made in the infrastructure to cope with the needs of level of service at the lower cost. This paper addresses the development and, in some extent, the implementation of PMS for the Portuguese international airport network and for national and municipal road networks. The networks were characterized for pavement bearing capacity, and using surface characteristics surveys and visual inspection campaigns. The PMS systems include an aid-decision tool using a deterministic performance model for the pavements. The aid-decision tool computes the best preventive strategy for the network maintenance. This decision-making process takes into account the current situation, the traffic forecasts, quality levels established by the manager and economic scenarios (in some extent). The entire system could be controlled through a web-based interface, where the manager can access to all information contained in the database and trigger the intervention plan and costs according to the analysed scenario. The paper describes different stages of development and adaptation of the system to meet the needs expressed by the infrastructure manager. It is also given a flavour of what it will be expect to develop within the next 3 to 5 years to come.

Keywords: Pavement Management System; aid-decision tool; web-based interface

1. Introduction

Due to the demanding requirements of performance and safety, transport infrastructure pavements must be ensured throughout its service life. These requirements, along with the increase of traffic, have triggered maintenance and repair needs. These coupled with budget constraints, led managers to address the performance and rehabilitation of the pavements in a more effective way.

Even for airport pavement management scope, the present limitations pop out when the regular “reaction to distress” approach was unable to be funded due to budget constrains [1]. Road and Airport management administrations were forced to deal with their infrastructures in a much more preventive than reactive approach [2].

In this context, developing a tailored PMS is the solution that not only responds to the necessary optimization of resources but also minimizes the interventions that interfere with the normal infrastructure operations [3].

2. PMS development

2.1 General structure

According to our experience, the developed systems for road or airport pavements were self-contained systems to be operated in one workstation [4].

In continuation, the system description taken as example was developed for an international network of airports as a web-based system [5], in order to allow remote access to all information for the pavement maintenance groups in the different airports. This was the same with the present systems for a national road network with different hierarchies but not for a local road network just for dimension reasons or for a motorways concession network for similar reasons.

The systems are generally developed over a geographical information system (GIS) layout that allows representation and use of all data, historical or the one resulting of the planned interventions.

In the case of airport pavement management system (APMS), recently developed, the structure was divided into five modules. The first module, "Administration", allows the definition of how the system will be used, by whom and for which infrastructure and system modules. It also allows that new features could be added at any time.

In the second module, "Import Data", users can deal with all type of necessary data related to the infrastructure layout and condition. This type of database contains information about the characterization of materials and pavements, traffic characteristics and volume and the expected demand trends, all included in a timeline.

The third module, "Query", allows the use of the results for all condition states surveyed. This information is presented in numeric form as well as in graphic form and is always represented in the network map, allowing the user to easily obtain information related to a certain section.

In the fourth and fifth modules, "Management" and "Evaluation" respectively, the user can manage the parameters to consider in the different scenarios to be tested by the evaluation model. For each of the scenarios, which can differ in the traffic prediction, pavement condition level to achieve and the macroeconomic constrains, the aid-decision model will calculate the optimal resource allocation on those conditions. The results of all studied scenarios are described in a report.

The manager, in order to decide about the plan for the pavement interventions with a time-span usually till the next five years, will use the support of the aforementioned report produced in module five and all the additional constrains that could not be included in the studied scenarios, which are related to unexpected policy changes within the managing structure.

2.2 Pavement condition survey

For the development of the system, an extensive and consistent along the time job of characterization of type of all infrastructures should be carried out to obtain the necessary knowledge concerning the pavements behaviour and its condition evolving. In the case of the APMS used as support of this description, the campaign took three years and it consisted of an exhaustive analysis of all the available documentation about construction and rehabilitation parameters, as well as numerous field surveys [6] (Picado-Santos and Abreu, 2012).

For the structural characterization of the airport pavements, a super heavy falling weight deflectometer survey was done together with foundation and pavement prospection jobs and laboratory tests, allowing the definition of the pavement's mechanical characteristics (Figure 1).

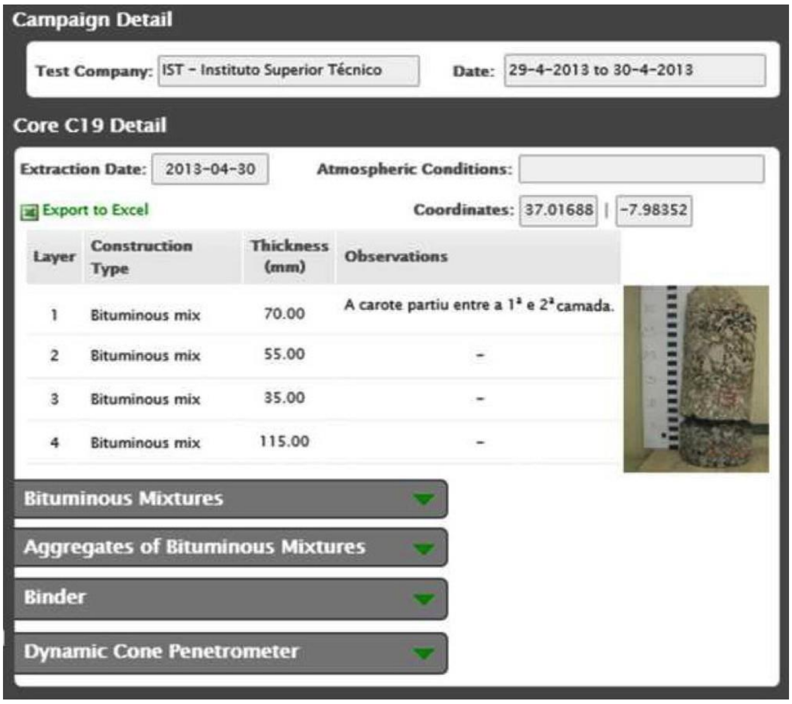

Figure 1: Example of the system screen layout for the registration of the obtained core characterization in laboratory

Some pavement surface characteristics, in operational areas, were obtained by doing a laser profiler survey that delivered IRI (International Roughness Index), ETD Texture (Estimated Texture Depth, equivalent to MTD/sand-patch method) and Straightedge [7].

A specific computerized tool was developed to assist in the visual inspection campaigns. Through its use, and complying with the ASTM D5340-14 Standard [8], all obtained data was georeferenced and ready to be loaded to the system database (Figure 2).

Skid resistance surveys and images that were captured by videography for all the infrastructures were also added to the database in order to deal with live safety issues and allow that some particularities could be checked directly in the system.

2.3 Aid-decision framework

The APMS' aid-decision framework uses a deterministic performance model to set the evolving of the pavement condition [9,10]. In terms of structure, the aid-decision framework is divided in three units – A, B and C – as shown in Figure 3.

In unit A, the information of the database, both historical and collected throughout the years of the characterization surveys, is then considered for each of the "Management Sections" (MS) considered as the managerial unit for each infrastructure. All MS here considered originate in the subdivision of each branch of an airport (runway, taxiway and apron) in order to guarantee homogeneity for structural and functional conditions, and traffic.

The creation of these MS allows the model to provide a more detailed solution, which helps the airport manager to adjust the interventions to the needs [11]. Unit A also includes all constraints. These can be divided in quality restrictions [12], measured in years of residual life, financial restrictions as the infrastructure update rate and operational restrictions [13]. The manager sets the planning period, necessary for the analysis, in this unit.

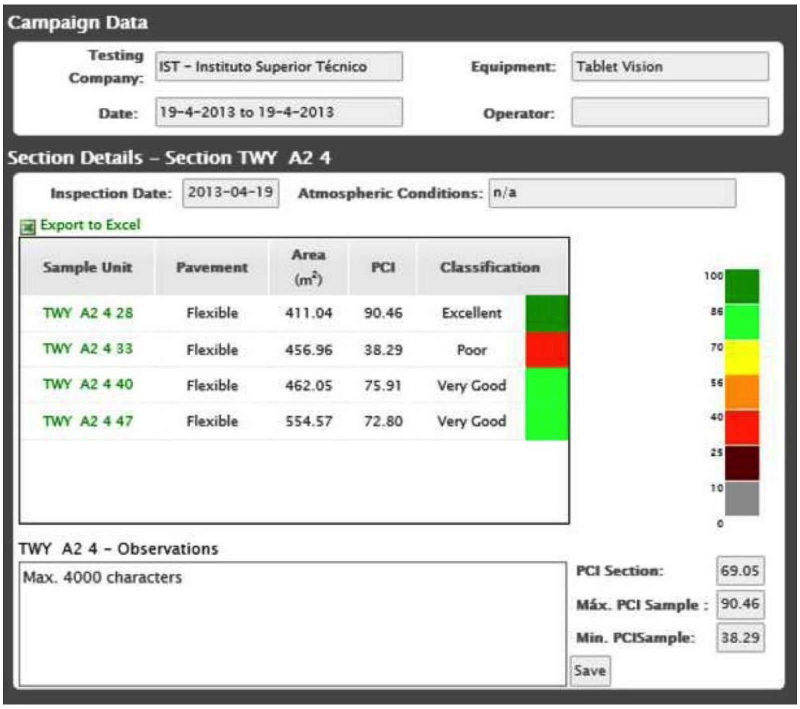

Figure 2: Example of the system screen layout for the registration of visual inspection campaigns

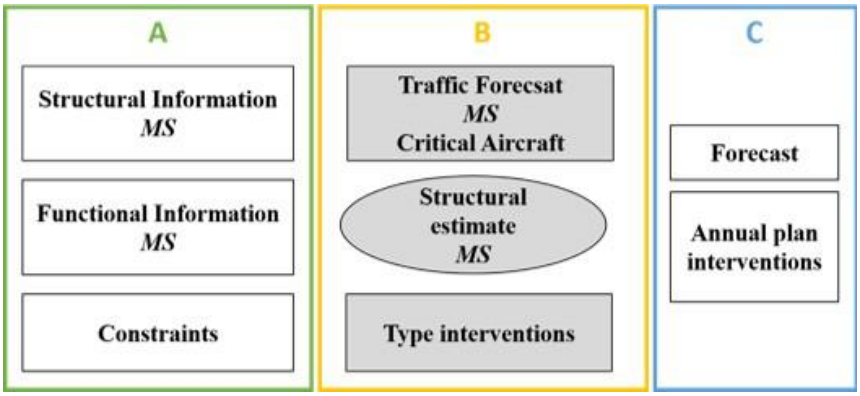

Figure 3: Structure of the aid-decision framework

The main quality restrictions are the residual life at the end of the planning period and at the end of each year. All the optimization process is carried out to meet the quality requirements represented by the chosen values that will be considered in the objective function. The minimum residual life that activates an intervention priority (when this value is reached the MS in question is intervened in the next period) and the minimum admissible residual life at the end of the planning period are regarded as quality constraints as well.

The update rate and the penalty for not respecting the quality restrictions are the only budget related constraints considered. The latter parameter represents the managerial costs of not observing the quality restrictions, which can represent some costly unplanned/emergency interventions for the future.

In operational terms, the constraints observed are the number of days an intervention can take place (excluding peak periods and/or adverse weather conditions) and the number of sections that can undergo an intervention in a specific year (this parameter intends to minimize the impossibility of intervention for operational reasons). Table 1 shows the list of all constraints.

In unit B (Figure 3), the prediction model for the pavement state is activated. To set this model it was used a neural network approach, calibrated for different critical type of vehicle (airplane for APMS) and different type of interventions over the pavement. Each APMS' MS is then subjected to traffic prediction according to the critical airplane for the specific airport infrastructure and the known growth rate for the traffic is assigned to each one. A catalogue of possible interventions is also available, characterized by their physical (type of materials and thickness) and structural characteristics, as well as [4] the productivity (m2/h) and unitary cost (€/m2) of each.

Constraint	Type of Constraint	Unit
Planning Period	-	Year
Intended Quality Objective for the section at the end of the analysis period	Quality	Year
Intended Quality Objective for the section in each year of the analysis period	Quality	Year
Penalty to restore the intended residual life in terms of cost in each section	Monetary	%
Minimum residual life (for activation of intervention priority)	Quality	Year
Update rate	Monetary	%
Minimum residual life at the end of the analysis period	Quality	Year
Maximum number of intervention days in a given year	Operational	-
Maximum number of sections with interventions in the same year	Operational	Day

Table 1: List of constrains used for the described APMS

In selecting the type of interventions, aspects as the location of the infrastructure [14], Portuguese technological practice [15,16] and practical experience for each infrastructure were taken into account.

The unit C (Figure 3) is where the different future possible scenarios are treated, taking into account constraints and information from the previous units. The best strategy is the one that best fits the material and financial resources available, in general the one that minimizes the total cost of the investment, fulfilling the quality requirements established. The annual plan, year by year of the planning period, includes the interventions described by type and MS, the pavement state and the budget needed.

Just as illustration, if an analysis period of 20 years is taken as well as the type of constrains described, in Figure 4 is possible to visualize the pavement condition evolving, actually represented by the pavement residual life. In Table 2 is possible to see the investment plan proposed by the model, which is comprised of forty- three interventions costing a total of 6,502 million euros. At the end of the planning period, the average residual life of the 78 MS considered was 6,6 years.

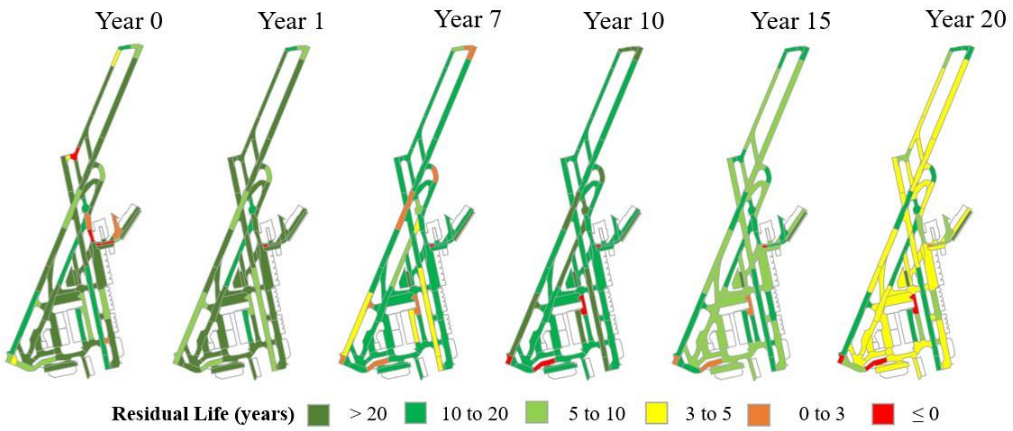

Figure 4: Example of the pavement condition evolving for an airport infrastructure

3. Conclusions

It can be stated that the developed APMS, after the implementation phase already performed by the manager, provides a deep knowledge about the infrastructures as the database, including present and future (resulting of the implementation of the best strategy possible) conditions, allows an easy and fast assessment of the pavements' condition.

With the implemented aid-decision tool, the manager can, besides the security and conditions checks (a daily basis concern for airports), evaluate the pavement conditions when subject to a specific traffic and investment scenario. This evolution measured in terms of the pavement residual life allows the adjustment of the investment plan at any time. In this way, the non-predicted alterations at the beginning of the planning period (for instances changes in traffic volume and typology or the infrastructure layout) can be easily added originating a new investment plan, more suitable to the situation. For each tested scenario a detailed report is elaborated with a number of proposed intervention plans, their costs and the influence of the chosen plan in the quality parameter of the area to intervene.

Year	Number of	Cost by year [millions of
1	14	1,487
2	1	0,093
5	1	0,093
8	1	0,093
10	13	2,988
11	1	0,093
12	3	0,574
14	1	0,093
15	3	0,401
17	1	0,093
18	3	0,401
20	1	0,093
Total	43	6,502

Table 2: Example of an investment plan proposed by APMS for the illustration related with Figure 4

Nevertheless, and specially for this APMS, some drawbacks should be stated as the fact that the pavement performance model showed to be quite sensitive to traffic estimates and its network distribution, generating significant additional costs when these estimates are overlooked for each MS. This could lead to a loop decision framework by the system, for example allocating the same intervention several times during the planning period due to excess of predicted traffic for an initial pavement structure in poor condition. Other aspect concerns the available time (maximum number of intervention days in a given year) for executing the planned interventions in a specific year. If it was not enough, the aid-decision tool moves that intervention to the following year and so on, generating an over cost due to the impossibility of carrying out the intervention at the right time (year).

The generally described APMS was a tailor-made system for the manager, developed according to his needs and requirements. The same happened with the different road network managers for whom similar systems were developed. This fact allows much more effective decisions about network maintenance, resulting in a more efficient use of human, material and financial resources.

Finally, according to our experience, the managers are pretty much dependent of the financial strategies of the top management of their organizations. In this sense, aspects as financial risks to support investment and consideration of uncertainty for the economic evolvement of a country, a region or even the world, should be introduced in the PMS analysis, together with other more technological type of risks and uncertainties. Planning with flexibility to adjust to different situations is the key issue for the next generationofPMS.

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Performance of Overall Maintenance Audit in Company

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Abstract
This article describes application of methodology for performance of complex maintenance audit in a company. All provided information comes from author's real experience from projects of consultancy in manufacturing and transportation industry.

Keywords: maintenance audit, maintenance management, maintenance improvement

Introduction

The essence of overall maintenance audit is to determine status of maintenance, and where appropriate, to get comparison to other businesses in industry. Its content is sequence of systematic activities (data collection, analysis, evaluation, site visit, monitoring, etc.), leading to provision of a comprehensive picture of state of maintenance management and execution in company (within agreed scope). Audit is non-invasive, this means that audit does not make implement any measures (changes are often implemented by subsequent stage). Audit is independent. Therefore, it is desirable to perform audit by unbiased external company. Audit is often performed in large companies possessing own production and large amount of machinery and equipment, for example petrochemical, automotive, energy, geo-mining or metallurgical industries.

Areas of Maintenance Audit

In this chapter are highlighted frequent areas as subject of investigation within framework of audit. However, as is mentioned in following chapters, scope and focus may vary from company to company and customer specific requirements. For each area we list the key points and possible outputs according to past experience.

Maintenance management
Maintenance strategy
Organization and human resources
Preventive maintenance
Maintenance planning and scheduling
Maintenance process execution
Information system support
Administration, documentation and reporting
Maintenance effectivity and continuous improvement

Planning process and inventory management
Analysis of current planning process
Current settings of MRP and division of items to managed and non-managed by MRP and reason for this division
Feasibility and benefit of setting up central planning process for all plants
Analysis of current calculation of safety stock and re-order point (min/max)
Import of MARS data to system Planning Wizard and calculation of new safety stock and re-order point

Information system material base
Analysis of quality of master data record for GRD material
Evaluation of current methodology of material naming convention and its fulfillment
Analysis of necessity and expediency of focal work to improve material base
Evaluation of current approach to classification of materials
Analysis of obsolete material and process for obsolete material elimination

Spare parts procurement process
Mapping of complex process of spare parts acquisition (including internal process from order placement till item consumption)
Existing procurement process map revision and evaluation of compliance with procurement execution in practice
Analysis of efficiency of current internal process of spare parts procurement, including tendering
Analysis of effectiveness of existing suppliers

Warehouse of spare parts
Analysis of compliance of current inventory on hand with actual need in all factories – calculation in Planning Wizard
Site visit and check of correctness of storage conditions
Identification of „squirrel/black warehouses“, if any (warehouses with items out of system evidence)
Analysis and identification of items with potential for centralization

Figure 1: Example: key areas of investigation during maintenance audit

Maintenance Audit is Project

Audit maintenance is always a project. As such, it is sequence of predetermined activities, bounded by defined time and allocated resources. Let's highlight some typical project features for maintenance audit:

Goals and Outputs

It is extremely important to set common expectations from results of the project by all participating parties. Especially, when audit is outsourced, it is necessary to describe and approve together with customer the desired state at the end of the project. To achieve this we define purpose, objectives and outputs of the project within preparation stage.

Purpose is a sort of higher goal of the project. By purpose we realize the root cause of our decision - we ask question "Why?". Answer can be simple, such as "To increase maintenance efficiency".

The purpose of the project is important for clarification of fundamental trigger. But, for project management, the Goals are much more important. Project goals are usually related to agreed Outputs, giving us ability to evaluate result/success of project and measure fulfillment of particular goals. Here we mention some typical general project goals for maintenance audit:

To identify potentials for improvement in maintenance management and execution
To evaluate potentials for improvement in terms of needed effort and resources for implementation against benefits achieved by implementation
To define detailed action plans for implementation of changes (size of investment, resources, process/structure changes description, time schedule of implementation with relevant tasks and responsibilities etc.)

To provide benchmark of maintenance management and performance whether internally - for example, between individual factories of a company, or externally - reference of other companies in industry or companies of same size and technology
Beside general goals, customer sometimes comes straight away with specific demand and requires to focus on specific areas. This is mostly related to actual situation in company, from where can arise, for instance, following specific customer related goals:
To map process of procurement of spare parts and to assess possibility and effects of centralization
To review spare parts stock levels and to provide necessary steps for stock levels optimization
To verify needed headcount for maintenance execution
To assess readiness for transition to new maintenance management information system
To examine effects of outsourcing of maintenance services
To examine and oppose tender documentation for selection of technologies for new spare parts warehouse

Project plan, Project Management and Cooperation

Project plan, also called project time schedule, is basic guideline and control element of project course. As such it must contain all key tasks and project activities, including deadlines and owners/responsible for particular tasks. Project tasks should be divided into project phases. In my company, we usually distinguish project tasks of maintenance audit into 3 basic stages:

Phase 0: Pre-analysis

This stage is also called diagnosis stage. In order to avoid delays at the beginning of project, we define input data requirements even before opening meeting (kick-off meeting). Virtually, every company has own structure of information resources of different size, detail and quality and different practices of data processing. Thanks to pre-analysis stage we are able to analyze input data in advance, allowing us to anticipate areas of system bottlenecks and to focus later more into detail. And, in case of findings of data deficiencies, we send complementary requirements on input data in timely manner. At the opening meeting, status of reception of input data is given and data content and accuracy is confirmed with customer. Examples of required input are following:

- Organization structure of maintenance
- Headcount in maintenance and roles (x years history)
- History of production stops due to technology (downtimes due to failures)
- OEE for lines or machines/equipment
- Percentage of equipment with preventive maintenance plan defined
- Ratio of preventive/corrective maintenance (corrective = repair after failure)
- Maintenance cost year by year (x years history)
- Value and quantity of spare parts inventory year by year (x years history)
- Number of spare parts items (indexes, material numbers) (x years history)
- Asset replacement value for maintained equipment (if available)

- List of critical spare parts (if there is any) and preventive maintenance plans for some
- Maintenance budget (x years history)
- Map of spare parts procurement process
- Standards, manuals, working guides, and other relevant documentation

Phase 1: Audit and Analysis

During this phase usually take place visits of operations. It may be one small factory, or several large plants in different countries as well. During visits on site it is necessary to conduct interviews with key representatives. The interviews are composed according to investigated area. During sessions we also refer to findings from input data analysis, thereby the findings are verified. It is also necessary to investigate and compare the regulations and rules with real working routine.

Predefined questions are not asked only to managers, it is necessary to speak also with people at lower levels of organizational structure. From past experience, subject to interview are, in particular: top managers, maintenance managers, maintenance planners, maintenance inventory planners, maintenance technicians, IT data specialists and master data administrators, maintenance shift masters and warehouse keepers. In many organizations, these roles often overlap.

Here comes one of essential conditions for successful audit – properly set and agreed cooperation of customer is essential. It is impossible to perform correct audit and provide quality outputs without engagement of people who manage and perform maintenance in company. Therefore, before start of project we have to state the needed capacity of individual roles and a timetable for visits and interviews. An employee will surely participate on audit in common working hours. So, it is important for superiors to know the expected utilization on the project. An illustrative timetable for maintenance audit of four production factories is shown in figure 2.

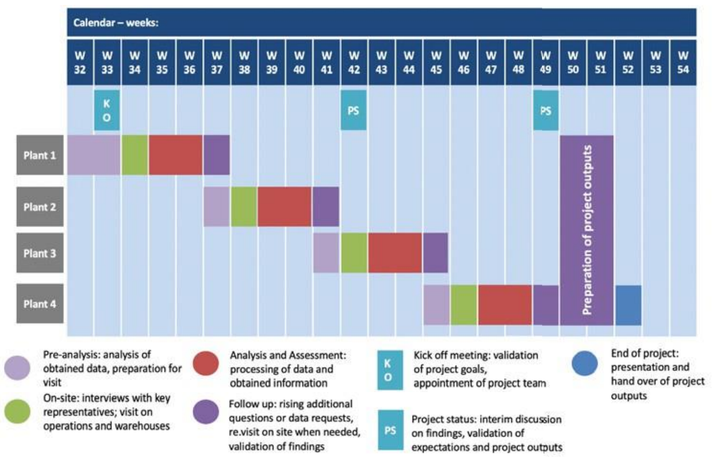

Figure 2: Example of maintenance audit timetable for four production factories

At the end of visits (or already during visits) the phase of Analysis and Assessment begins, where all collected information should be processed and summarized. In this stage, open points usually appear - requesting certain follow up in form of additional questions addressed to specific departments/persons, or complementary visit/ sessions of specific topic.

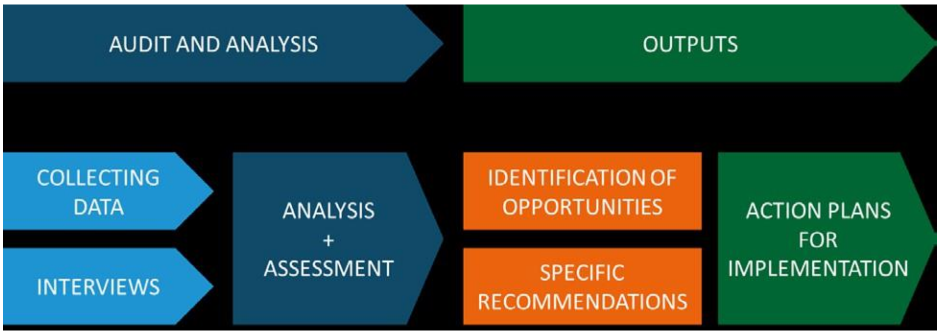

Figure 2: Maintenance audit main activities process scheme

Phase 2: Outputs

Once there is sufficiency of needed information, we can proceed to formation of outputs. Opportunities identified during data collection and site visits are subject of description and quantification. Understandable and simple imaging tool is graph in figure 3. Each number represents one potential for improvement, which is evaluated in terms of necessary investment (time, money, resources) against obtained benefits.

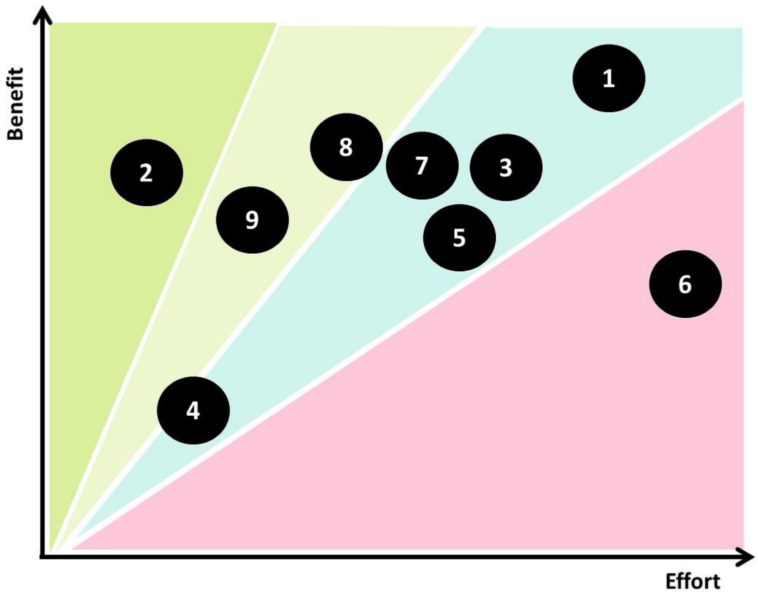

Figure 3: Chart interpretation of potentials of improvement

The potentials of improvement for company are following:

Ratio of preventive/corrective maintenance is 30%/70%

Insufficient personnel in certain departments to cover maintenance jobs

Spare parts inventories are insufficient

Maintenance material is not properly stored

There is no common methodology for spare parts naming (causing duplicities and confusion)

Storage of documentation is mostly not computerized and centralized

There is no list of critical spare parts and defined minimum stock levels

There is no division of low-skilled work from advanced tasks (lack of maintenance pool)

For clarity, potential for improvement number 9 is further elaborated:

Procurement process is complex and slow

There is potential to speed up procurement processes so needed spare parts are delivered as soon as possible. Amount of framework contracts with key suppliers is limited and contracting is done for each single part. Wise and fast procurement of spare parts will reduce delays in maintenance and will enable maintenance to reduce MTTR (repair times) and resulting downtimes. In figure 4 is example of more detailed action plan including expected scope, benefits and needed resources.

<table>
<tr><td>Project ID</td><td colspan="3">Project title:
Spare parts procurement improvement</td></tr>
<tr><td colspan="2">Proposed kick-off date: 1/12/2017</td><td colspan="2">Expected project end: 28/2/2018</td></tr>
<tr><td colspan="4">SITUATION:
Maintenance in many departments is often delayed due to lack of necessary spare parts. This is caused by problems/obstacles in the procurement process that make internal order and delivery time inappropriately long. These spare parts will be purchased sooner or later anyway, so no saving is achieved by prolonging duration of procurement.</td></tr>
<tr><td colspan="4">SPECIFICATION OF CHANGE:
• Improve procurement process so there are no unnecessary delays and obstacles to buy spare parts needed for maintenance.
• Utilize possible synergies with XXX (spare parts pooling, joint contracting maintenance)</td></tr>
<tr><td colspan="4">EXPECTED BENEFITS:
7. Needed maintenance of critical equipment can be done on time
8. Reduction of downtimes
Production uptime improvement due to preventive maintenance: 1 min = 75000 RUB
(1 hr = 4 500 000 M RUB)</td></tr>
<tr><td colspan="3">OBJECTIVES
Reduce internal lead time (administration delay) in procurement for critical items</td><td>Value
10-50%</td></tr>
<tr><td colspan="3">PROJECT PLAN/TIMETABLE:</td><td>Deadline</td></tr>
<tr><td colspan="3">Procurement process mapping and analysis</td><td>19. 12. 2017</td></tr>
<tr><td colspan="3">Identification of problems in process</td><td>31. 12. 2017</td></tr>
<tr><td colspan="3">Identification and analysis of potential synergies with XXX</td><td>16. 1. 2018</td></tr>
<tr><td colspan="3">Elimination of identified problems – proposal of future state process map</td><td>16. 1. 2018</td></tr>
<tr><td colspan="3">Implementation of changes</td><td>20. 2. 2018</td></tr>
<tr><td colspan="3">Evaluation of changes</td><td>28. 2. 2018</td></tr>
<tr><td colspan="4">PROPOSED TEAM:
Project expert Logio: T. Hladik
Project coordinator Logio: T. Kubina</td></tr>
<tr><td colspan="4">REQUIRED RESOURCES ESTIMATE:</td></tr>
<tr><td>CAPEX
OPEX
Workload (internal)
Duration (trasnition period)</td><td colspan="2">None or minor
None
PM x 1 days/w, Procurement manager 1 d/w, 3 Buyers x 12 days
3 months (13 weeks)</td><td>0
0
62 mandays</td></tr>
<tr><td>DATE: 6/11/2017</td><td>PROPOSED BY:
Tomáš Hladík, LOGIO</td><td colspan="2">PREPARED BY:
Tomáš Hladík, LOGIO</td></tr>
</table>

Figure 4: Detailed action plan of Spare parts procurement improvement

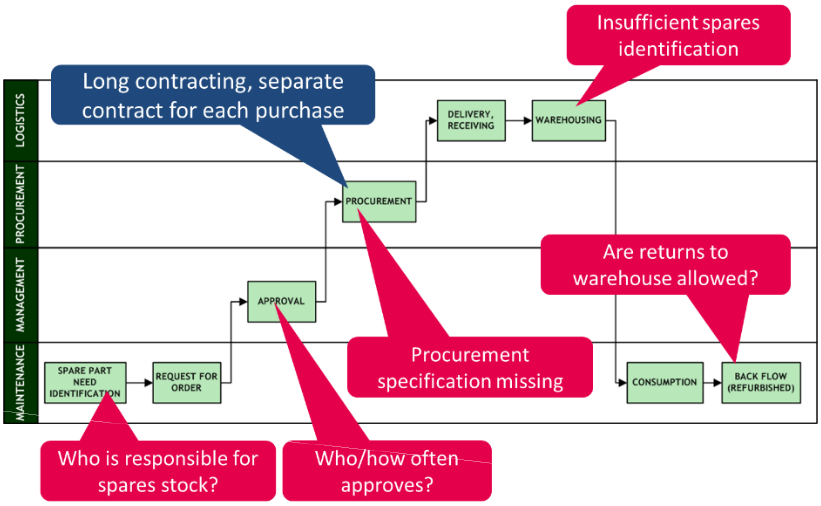

Figure 5: Management summary of recommendations for spare parts procurement

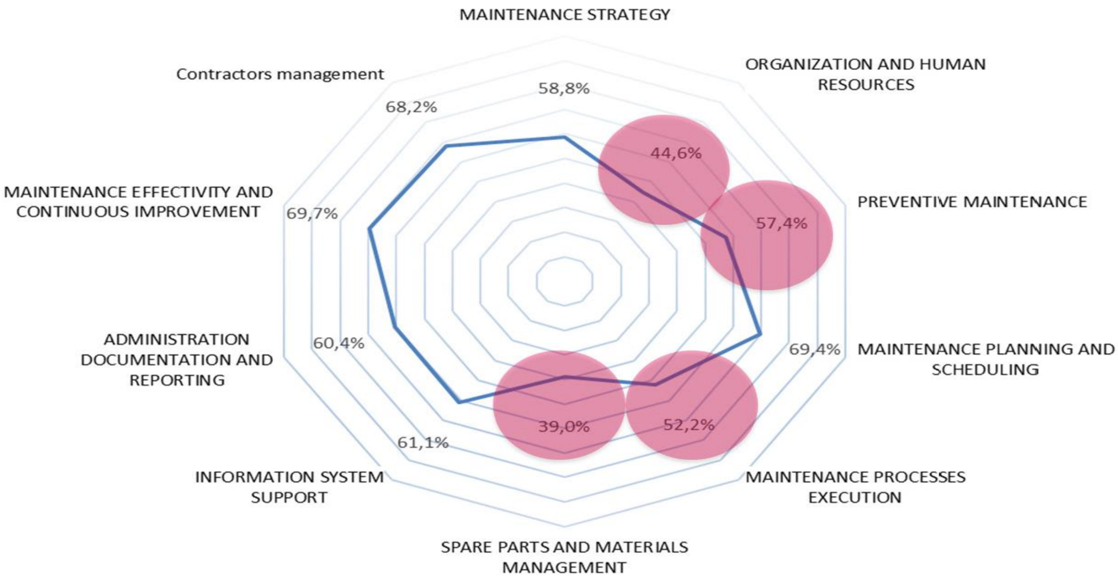

Figure 6: Example of chart summary interpretation of potentials of improvement

Conclusion

Maintenance audit is an effective tool to analyze actual situation in company, to identify chokepoints, and to define of next steps to improve maintenance management. However, it crucial to perform it according to predefined process and methodology, to correctly estimate necessary resources of all parties, and to define clear objectives. At the very conclusion we would like to summarize some of pitfalls and opportunities, collected during audits, which can help potential solvers.

Manage Audit as a project!

Maintenance is a broad field and you should define and agree scope, goals and outputs of audit before the project starts. You will avoid later inconsistencies in anticipation of you and customer.

Maintenance is not isolated discipline

In company, maintenance is closely related to production/operations, purchasing and logistics. It is necessary to predict and observe tensions and development in between departments and always seek solutions for the whole system. One of added values of consulting company should be the link between departments and arrangement of joint discussions and workshops to achieve satisfaction of all parties.

Be prepared to help with implementation

The best confirmation that the proposed solutions are feasible is an offer for cooperation on implementation. And, the customer is certain you know the company environment and understand proposed solution.

Speak with all levels of employees

You should obtain view of people running business on a strategic level, but also ordinary maintenance workers and buyers. Ask people on their problems. They often have great ideas for improvement that are just never heard. At the same time, it should be borne in mind that only presence of auditor causes higher efficiency and out of fear they don't tell the whole truth.

Focus on detail where you feel opportunity/bottleneck

In majority of audits it is simply impossible to go through everything. You need to focus on weak areas. They often sound on sessions with management, are mentioned in assignment or uncovered by preliminary analysis and experience.

OMAINTEC Journal
(Journal of Scientific Review)

Enhancing Rigid Pavement Quality with the Aid of Bacteria

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Abstract

Microcracking of rigid pavement usually occur due to the shrinkage of concrete after casting or throughout its service life due to repeated compressive, tensile, and shear stress. Such cracking exhibit a durability problem since the ingress of moisture and harmful chemicals such as sulphates and chlorides into the concrete through the cracks can cause premature matrix degradation and corrosion of embedded steel reinforcement, which may result in the decrement of strength and life. In this work, implementation of self-healing techniques was adopted with the aid of bacteria and healing agent to precipitate CaCo3 on the formed micro-cracks. The precipitation of calcite by continuous hydration of cement helps in production of calcium carbonate precipitation with the help of bacteria. A soil bacterium named Bacillus subtilis was cultured in the laboratory, the concentration of bacteria cell of B. subtilits in normal saline (NaCl, 9 g/l) suspension was 106 cell/ml. Concrete specimens of various type (cube of 100x100x100 mm, cylinder of 100mm diameter and 200mm height, and beam of 100 x 100 x 500 mm) size have been prepared in the laboratory, then separated to three sets. The first set of specimens were subjected to controlled compression and flexure pre-cracking, then subjected to healing and curing in a water bath which contains the prementioned bacteria at 20°C for 7 days. The second set was the control specimens cured in water bath for 7 and 28 days at 20°C. The third set of specimens were subjected to healing and curing in a water bath which contains the prementioned bacteria at 20°C for 7 and 28 days and then tested for compressive, indirect tensile, and flexure properties. It was observed that the healing process provided by the bacteria have improved the overall properties of concrete by (23, 10.7 and 16) % for compressive, tensile and flexure strength respectively as compared to those of control mixture after 28 days of curing. On the other hand, specimens subjected to controlled pre-cracking exhibit improvement in strength properties after the healing process provided by the bacteria by (28 and 33) % for compressive and flexure strength respectively as compared to those of control mixture after 7 days of curing. It was concluded that implementation of the healing concept of cracking with the aid of bacteria is beneficial and can be considered as sustainable and environment friendly solution for maintenance.

Keywords:

Maintenance, concrete, bacteria, healing, pre-cracking, pavement

1 Introduction

Concrete is the most commonly used material for construction of rigid pavement for airport and major arterials in Iraq. Micro Cracks usually occurs due to various mechanisms such as temperature gradient of thick pavement, repeated loading, shrinkage after casting, and Freeze-thaw cycles. Maintenance of cracks of macro size is a routine work, but the problem arises when micro cracks exists as stated by Sarsam, [10]. Cracks tend to expand further and eventually require costly repair. If micro cracks grow and reach the reinforcement, the reinforcement may corrode when it is exposed to water and oxygen and possibly carbon dioxide and chlorides (indirect degradation) as reported by Nivedhitha, et al, [6]. Research has shown that autogenous healing happens due to hydration of non-reacted cement particles present in the concrete matrix when encounters ingress water resulting in closure of micro cracks, the inbuilt bacteria-based self-healing process was found to heal cracks completely up to 0.5 mm width, Rao et al, [9]. Novel technique has been developed by using a selective microbial metabolic activity promote calcium carbonate (calcite) precipitation, Karthik and Rao, [4]. At the point when broken segment blended in microscopic organisms interacts with fresh concrete, cracked surfaces are enacted within the sight of water, and after that starts to multiply and precipitate minerals. These minerals, including calcium carbonate close the crack. The microscopic organisms should act as an impetus and change an antecedent compound, for example, calcium carbonate-based mineral accelerates, into an appropriate filler material, Vipu et al, [13]. Bacterial concrete helps in increase the strength of concrete by the action of calcium precipitation of bacteria and it proves to be cost effective. Bacterial concrete increases compressive strength up to 20%. The economical dose found by analysis is 10 ml that helped to make bacterial concrete quite economical. The cost of bacterial concrete increased 7-15% more than conventional concrete, Patil et al, [7]. It was stated by Prabakar et al, [8] that the use of bacterial concrete is one of the ecofriendly techniques for crack healing. This technique uses the calcium precipitate produced by bacterial metabolic activities to heal cracks. Bacterial concrete shows greater strength and durability than normal concrete. The addition of bacillus Subtilis bacteria showed significant improvement in the compressive, split tensile and flexural strength than the conventional concrete. From the above it can be concluded that bacteria can be easily cultured and safely used in improving the strength characteristics of concrete, Sarsam et al, [11]. The outcome of a study by Schlangen et al, [12] shows that crack healing in bacterial concrete is much more efficient than in concrete of the same composition but without added biochemical healing agent. The reason for this can be explained by the strictly chemical processes in the control and additional biological processes in the bacterial concrete. It was concluded by Bhagyashri et al, [2] that the greatest improvement in compressive strength occurs at cell concentrations of 105 cells/ml for all ages. The study showed that a 25% increase in 28-day compressive strength of cement mortar was achieved. Enhancement of compression strength, reduction in permeability, water absorption has been seen in various cementitious and stone materials. The nutrients for the bacteria which can precipitate calcite are calcium sources, phosphorous and nitrogen sources. These bacterial components remain dormant in concrete, when the seepage of water take place into the formed cracks helps in reacting with the nutrient to precipitate calcite i.e., CaCo3, Breugel, [3]. Bacterial induced calcium carbonate deposition has been proposed as an alternative and environmentally friendly crack repair and self-healing technique. The precipitation of Ca Co3 helps in sealing the micro cracks. It concluded by Krishnapriyaa et al, [5] that bacteria are suitable for use in concrete as it had resulted in increased strength and complete healing of cracks in concrete specimens. The inclusion of these bacteria in concrete will result in high strength, crack free and durable concrete structures in the future.

Based on the above introduction, the present investigation will consider implementation of Bacillus subtilis in the curing water of concrete to study its influence on the compressive, tensile, and flexural strength of concrete before and after pre-cracking.

2 Material Characteristics

2.1 Cement

The Iraqi Ordinary Portland cement (type 1) with a commercial name of (Tasluga) was implemented throughout the present work. Table 1 exhibit the chemical composition of cement, while Table 2 presents the physical properties of cement.

Oxide	% by weight	Limit of Iraqi specification No.5/ 1984
CaO	61.28	--------
SiO2	18.372	--------
Al2O3	3.58	--------
Fe2O3	5.02	--------
MgO	1.39	< 5.0
SO3	2.02	< 2.80
C_3A	0.988	--------
Loss on ignition	2.85	≤ 4.0
Insoluble residue	1.07	< 1.5
Lime saturated Factor	1.0148	≥ 0.66 ≤ 1.02

Table 1. Chemical composition of cement

Physical properties	Test result	Limits of Iraqi specification
Specific surface area, Blain's method m^2/kg	394	≥ 230
Soundness, Autoclave's Method, %	0.03	< 0.8
Setting time, Vicat's method		
Initial setting hour: min	2:15	≥ 45 min
Final setting hour: min	3:30	≤ 10 hours
Compressive strength		
3 days N/mm^2	20.7	≥ 15
7 days N/mm^2	26.1	≥ 23

Table 2. Physical properties of cement

2.2 Aggregate

Crushed gravel with a nominal size of (19 mm) was obtained from Nibaee region and used in this work. The properties of coarse aggregate are shown in Table 3. Fine aggregate of maximum size 4.75mm was obtained from Al-Ukhaider quarry and used, the properties of fine aggregate are shown in Table 3. The combined gradation implemented is illustrated in Table 4.

Type of aggregate	Bulk Specific Gravity	Density(kg/m³)	Absorption %	SO3 %
Crushed aggregate	2.63	1646	1.167	0.034
Fine aggregate	2.5	1789	9.3	0.126

Table 3. Properties of coarse and fine aggregates

2.3 Water

The water used in mixes was drinking water of Baghdad area. This water was also used for curing.

Sieve size mm	19	12.5	9.5	4.75	1.18	0.3	0.15
Percentage finer by weight	100	85	70	59	46.4	16	3.3

Table 4. Combined gradation adopted

3 Methodology

The methodology implemented in this investigation consist of three steps, in the first step, Culture and growth of bacteria (Bacillus subtilis) in the laboratory was conducted. The second step was preparation of concrete specimens (cubes, cylinder and beams), and pre-cracking was applied for cubes and beam specimens. In the third step, curing of the specimens was conducted in bacterial water then the strength properties of concrete specimens were evaluated after seven and 28 days of curing.

3.1 Preparation, Isolation and Culture of Bacteria Bacillus Subtilis

The isolation and culture of bacteria bacillus subtilis starts by collection of soil samples from Agricultural areas in Baghdad city and evacuation in glass bottles. The soil sample was then mixed with distilled water and shaken vigorously to ensure thorough mixing. Serial dilution was made by transfer of 1 ml of soil suspending to 9 ml of distilled water in test tube, this soil suspension is of 10-1 dilution. After mixing this solution in vortex mixer, one ml of 10-1 dilution was transfer to 9 ml of distilled water, then the concentration of solution becomes 10 -2 dilutions. This process was repeated until 10-6 dilution is obtained. After all these steps, petri-dishes plates with nutrient agar media according to the bacteria requirement have been prepared. The solution of concentration 10-4 to 10-6 was spread by cotton swab on the petri-dishes plate with nutrient agar media in it and incubated in 37 °C to 24 hours in the incubator. After 24 hours, the plates are taken out from incubator, the type of colony formation in the Petri dish plate was checked. Some more petri-dishes plates with the same media and soil sample with different concentration have also been prepared. After this, the different type of colonies on different plates were observed and the growth after 24 hours incubation was checked. The morphology of different colonies was checked by gram staining method. The urease test method and vitek 2E compact system have been implemented for identification of bacillus subtilis. Afterword, Preparation of the concentration 10 6 of bacterial cell (bacillus subtilis) starts by Transfer of loop full of single colonies of bacillus subtilis that form urease enzyme from nutrient agar to brain heart broth media and incubation at 37 °C on shaker at 150 rpm for 24 hours. The harvest of bacterial cell was done by centrifuge the 24 hour's old grown culture (5000 rpm, 5 minutes). The sediments (bacterial cell) was form after centrifuge and were re-suspended in normal saline (NaCl, 9 g/l). The concentration of bacteria cell of bacillus subtilits in suspension was 106 cell/ml. Figure 1 exhibit the isolation of the bacteria, while Figure 2 shows the culture and dilution of the bacteria.

Figure 1. Isolation of the bacteria.

Figure 2. Culture and dilution of the bacteria

3.2 Preparation of Concrete Mixture

Control concrete mixture was designed as per ACI 211.1-91, [1] method, such mixture is usually used for rigid pavement construction. The mix proportion is (1:1.5:3.75) with 0.45 water cement ratio. Cube, beam and cylinder specimens have been prepared, covered with polythene sheets to retain the mixing water for curing for 24 hours. Specimens were immersed in water with bacterial concentration of 106 cell/ml of water. Calcium lactate of 5% by weight of cement were added to the bacterial water. Specimens were tested after seven and 28 days to assess the impact of curing in bacterial water on the physical properties.

3.3 Pre-cracking of specimens

To simulate the concrete condition during service in the field, and to determine the effectiveness of bacteria in the crack healing process, specimens were subjected to controlled pre-cracking in the laboratory. Many trial specimens have been subjected to various compression and flexural loading, then tested for strength to check that it does not reach the failure condition. Cube specimens were subjected to pre-cracking after 24 hours of curing, a load of 260 kN was applied for one minute then released. Cube specimens were subjected to ultrasonic wave traverse with the aid of pundit to determine the time required for the sound to traverse the specimen before and after the pre-cracking process. For beam specimens, the pre-cracking was conducted using a flexure load of 5kN, while the ultrasonic wave traverse along the length of the beam. The time required for the sound to traverse the specimen before and after the pre-cracking process was recorded.

4 Results and Discussion

4.1 Ultrasonic Wave Traverse Time

Cubes and beam specimens have been subjected to ultrasonic wave traverse time determination before and after pre-cracking process and after bacterial curing to assess the influence of bacterial curing in the crack healing process. Control specimens were also tested for comparison. Figure 3-a exhibit the impact of bacterial curing on the ultrasonic wave traverse time for cube specimens. It can be observed that longer time was required to traverse the control cube specimen as compared to bacterial curing cube before pre-cracking, this may be attributed to the lower voids after bacterial curing due to precipitation of $CaCo_3$. After pre-cracking, the time taken by ultrasonic wave to traverse the cube was higher by (110 and 150) % for control and bacterial cured cubes respectively as compared to the case before pre-cracking. After seven days of curing, the variation of the ultrasonic wave traverse time was not significant among control and bacterial cured cubes. This could be attributed to the possible autogenous healing happens due to hydration of non-reacted cement particles present in the concrete matrix when encounters ingress water resulting in closure of micro cracks as mentioned by Rao et al, [9]. On the other hand, the curing period of seven days was effective in healing the microcracks for both control and bacterial cured cubes and the ultrasonic wave traverse time was almost equivalent to that before pre-cracking condition. Figure 3-b exhibit the impact of bacterial curing on the ultrasonic wave traverse time for beam specimens. After pre-cracking, the time taken by ultrasonic wave to traverse the beam was higher by (20) % for control and bacterial cured beams respectively as compared to the case before pre-cracking. After and before seven days of curing, the variation of the ultrasonic wave traverse time was not significant among control and bacterial cured beams. This may be explained that on the surface of control concrete, calcium carbonate will be formed due to the reaction of CO_2 present with calcium hydroxide present in the concrete matrix. The curing period of seven days was effective in healing the microcracks for both control and bacterial cured beams and the ultrasonic wave traverse time was 8% lower than that of after pre-cracking condition.

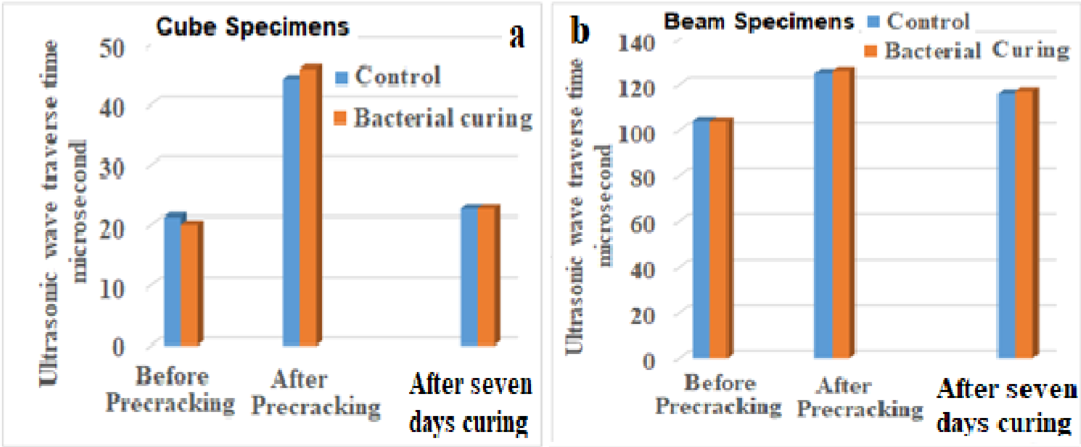

Figure 3. Ultrasonic wave traverse time for pre-cracked specimens

Figure 4. Ultrasonic wave test process

4.2 Strength Properties After Pre-Cracking

Six cubes are tested after a curing period of 7days, 28days, for every age period 3 cubes are casted. Control cubes were also prepared and tested for comparison. The size of cube is (100x100x100) mm. Beam specimens of (100 x 100) mm of section and 500 mm length have been prepared and tested in duplicate. Figure 5 exhibit the flexural and compressive strength of the pre-cracked specimens after seven days of curing in bacterial water, it can be noticed that the compressive strength increases by 28.5 %, while the flexural strength increases by 33 % after curing in bacterial water for seven days.

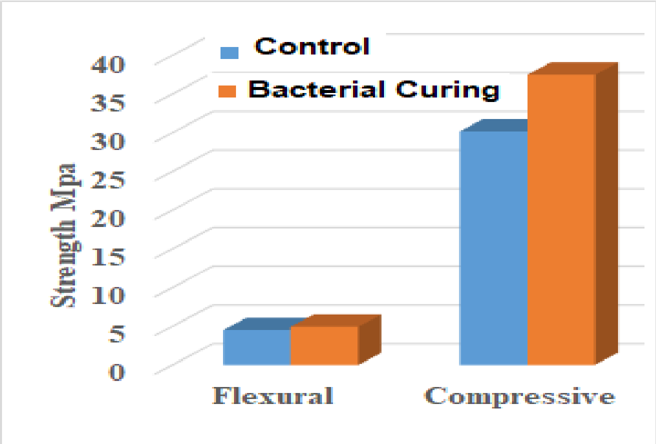

Figure 5. Strength properties after pre-cracking and curing for seven days

4.3 Specimens for Compressive Strength Test

Figure 6 shows the compressive strength determination of cube specimen. The compressive strength test results for both conventional and bacterial cured concrete are shown in Figure 8-a. It can be observed that the bacterial cured concrete exhibit high compressive strength when compared to that of control concrete. The variation was (107 and 23) % after 7 and 28 days of curing respectively. On the other hand, the increment in compressive strength after 28 days of curing was (95.5 and 18.4) % for control and bacterial concrete respectively.

4.4 Specimens for Splitting Tensile Test

Figure 7 shows the Indirect (splitting) tensile strength determination of cylinder specimen. The test is carried out after casting and curing cylindrical specimens of dimension 100mm diameter and 200mm height, specimens were tested for indirect tensile strength. The load was applied until failure of the specimen along the vertical diameter. The tensile strength was calculated based on the failure load. It can be noticed from Figure 8-b that the bacterial cured concrete exhibit high tensile strength when compared to that of control concrete. The variation was (5 and 10.7) % after 7 and 28 days of curing respectively. On the other hand, the increment in tensile strength after 28 days of curing was (8.3 and 14.2) % for control and bacterial cured concrete respectively.

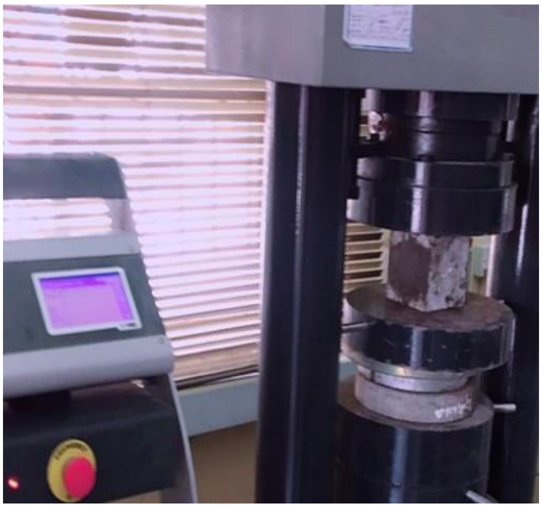

Figure 6. Compressive strength test

Figure 7. Indirect Tensile strength test

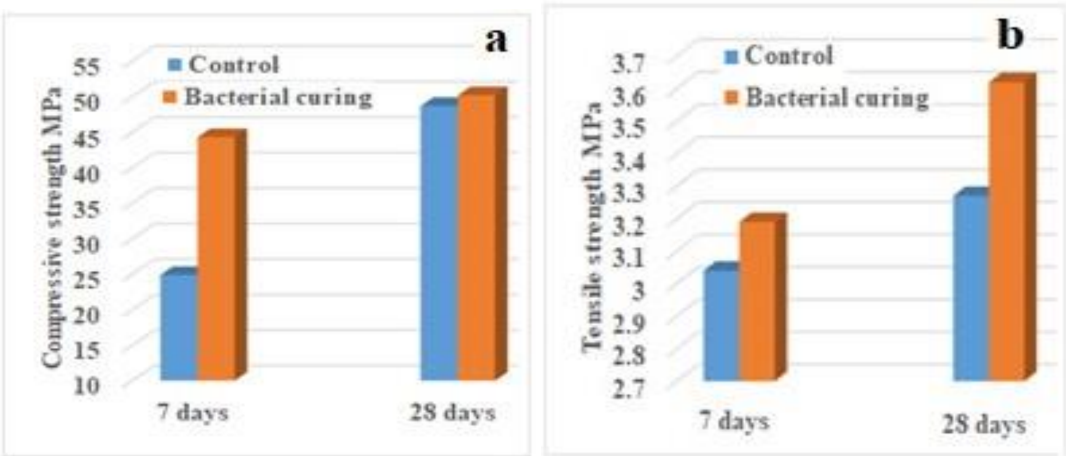

Figure 8. Compressive and Tensile Strength of pre-cracked specimens

4.5 Specimens for Flexural Strength Test (four-point loading)

The test is carried out after casting and curing beam specimens in bacterial water to find the flexural strength of the concrete. Control specimens were also prepared and tested for comparison. The beam specimens were placed in the machine in such manner that the load is applied to the uppermost surface as cast in the mold. Two points loading was adopted on an effective span of 450 mm while the beam rest on two supports. The load is applied until the failure. Figure 9 exhibit the flexural strength setup while Figure 10 shows the flexural strength of control and bacterial cured concrete. It can be noticed that the bacterial cured concrete exhibit high flexural strength when compared to that of control concrete. The variation was (22.5 and 16) % after 7 and 28 days of curing respectively. On the other hand, the increment in flexural strength after 28 days of curing was (38 and 48.7) % for control and bacterial cured concrete respectively. Such behavior may be attributed to the micro crack healing by precipitation of $CaCO_3$ in the microcracks.

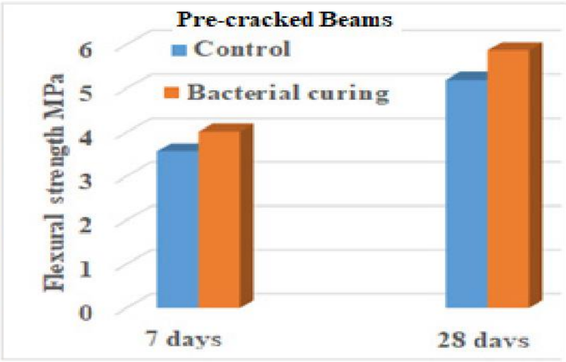

Figure 9. Flexural strength test

Figure 10. Flexural Strength of specimens

5 Conclusions

Based on the testing program, the following conclusions can be drawn

1- Implementation of bacteria (Bacillus subtilis) in the curing water exhibit a positive influence on the strength properties of concrete.

2- Bacterial cured concrete exhibit high compressive strength of (107 and 23) % after 7 and 28 days of curing respectively when compared to that of control concrete. The increment in compressive strength after 28 days of curing was (95.5 and 18.4) % for control and bacterial concrete respectively.

3- Bacterial cured concrete exhibit high tensile strength of (5 and 10.7) % after 7 and 28 days of curing respectively when compared to that of control concrete. The increment in tensile strength after 28 days of curing was (8.3 and 14.2) % for control and bacterial concrete respectively.

4- Bacterial cured concrete exhibit high flexural strength of (22.5 and 16) % after 7 and 28 days of curing respectively when compared to that of control concrete. The increment in flexural strength after 28 days of curing was (38 and 48.7) % for control and bacterial concrete respectively.

5- Specimens subjected to controlled pre-cracking exhibit improvement in strength properties after the healing process provided by the bacteria by (28 and 33) % for compressive and flexure strength respectively as compared to those of control mixture after 7 days of curing in bacterial water.

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Monetizing Data in Maintenance: Data-driven Spare Parts Management

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Abstract
Today, Digitization, Industry 4.0 and Maintenance 4.0 bring about vast volumes of data. Technologies like IoT or IIoT allow large sets of devices to connect to data networks and send complex data continuously. Organizations now keep huge amounts of data, structured or unstructured. However, from research of renowned organizations like Gartner we know, that industrial firms today are not able to use 70-90% of data that are collected and stored. This paradox is described in the paper, and various generic models of big data monetization are proposed. Some of these models are shown on examples from spare parts management.
Spare parts inventory can lock in significant amounts of working capital. This paper summarizes recommendations for effective spare parts inventory management and spare parts optimization using various sets of data and statistical analytical methods.
Keywords: Digitization, IoT, IIoT, Monetizing, Spare Parts Management

Introduction

Management of spare parts and other materials needed for realization of maintenance processes is one of the key functions in physical asset management. Especially in power generation, oil and gas and heavy chemical industries, spare parts inventories can easily add up to tens of thousands of various items, in a value of hundreds of millions of euros. It is obvious that efficient spare parts inventory management can have significant impact on the financial performance of the company. Better spare parts management can lead to improvement of financial performance of the company. In previous research we discussed several recommendations for spare parts inventory management. Using these recommendations, companies can achieve better financial performance in different parts of the spare parts lifecycle. In some of these recommended practices, various data can be employed and analyzed – especially in areas like portfolio segmentation, criticality assessment, forecasting, improving spare parts naming and identification, or cleaning and rectifying master data.

Eight rules of good spare parts management

In our previous research, we refined the following eight rules – best practices – for good spare parts management:

Focus on preventive maintenance – for preventive maintenance no inventories of spare parts need to be held.

Solve problems in spare parts processes.

Segment your spare parts portfolio.

Evaluate spare parts criticality.

Use suitable forecasting methods and verify their accuracy and reliability.

Use special methods for intermittent demand items.

Consider the whole lifecycle of your assets while making decisions related to spare parts.

Implement a good information system for spare parts management so all above stated rules are supported and/or automated.

Some of these rules are described in detail in the following chapters.

Each item is different: Segment your spare parts portfolio

In almost any inventory, different groups or segments of items can be identified. The primary objective of segmentation is to effectively divide an extensive portfolio of items on stock into separate groups requiring a different inventory management system, approach in planning, or specific optimization methodology. A good spare parts management information system allows for carrying out such analyses and portfolio segmentation quickly and easily, including visualization of outputs.

For inventory segmentation, a number of methods and criteria can be applied:

ABC analysis of inventory based on quantity and value available on stock (Fig. 1) and other criteria

ABC analysis according to item consumption (Fig. 2)

Segmentation based on frequency of consumption (identification of slow-moving inventory) in quantity or value (Fig. 3)

ABC analysis according to item criticality

Categorization based on item accessibility (common, special, made-to-order)

Identification of intermittent items (special test of intermittent demand)

Segmentation based on suppliers' leadtimes

For ABC analyses in case of spare parts, the prevalence of categories C and D (items with low or zero consumption in long-term history) is very typical.

Using segmentation based on consumption frequency, slow-moving inventory (SMI, items with minimum turnover, including “dead stock”) items can be promptly identified (Fig. 3). For spare parts, the 0 segment is usually the most important. This segment covers items with no consumption record in the past 12 months. Segment 0 is generally the most significant both in quantity and in value. It includes items of strategically important and critical spare parts – items with the highest value in the portfolio. Other segments with low frequency of demand are also significant (segments 1, 2, etc.). Segments with frequent consumption (segments 10, 11, 12) contain items of fasteners with relatively low value (Fig. 3).

The segmentation may also include specification of links between spare parts and appropriate production equipment (technical site). Bills of material, obtained in this way, make it possible to closely trace spare parts consumption for individual parts of production equipment, measure costs in each stage of the production equipment life-cycle, and identify critical spare parts in relation to the criticality of production equipment.

For each identified inventory segment (or for each individual item, if possible), the required level of availability (service level) needs to be specified. The desired logistic service level is closely related to the spare part's criticality: for highly critical items a service level of, for instance, 99.7% will be required. Obviously, there is a trade-off involved: the higher service level that is required, the higher minimum level of inventory is needed.

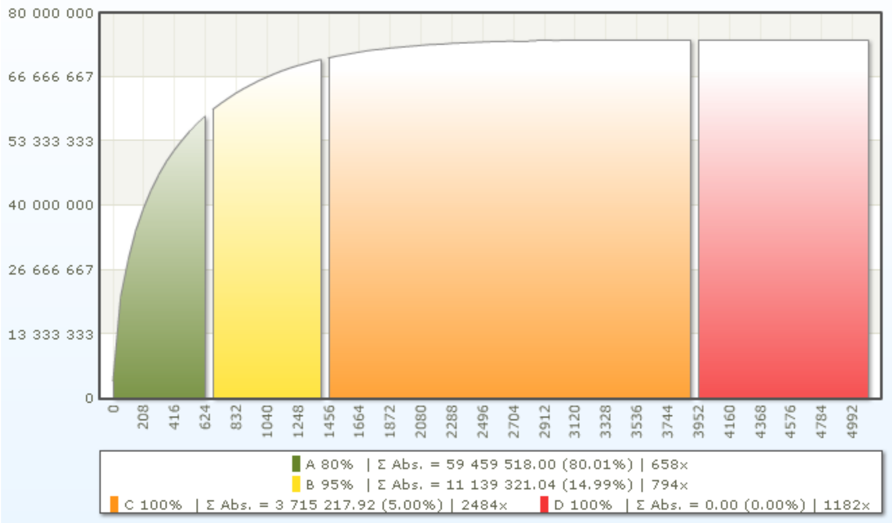

Figure 1: ABC analysis of spare parts inventory based on available stock value [CZK].

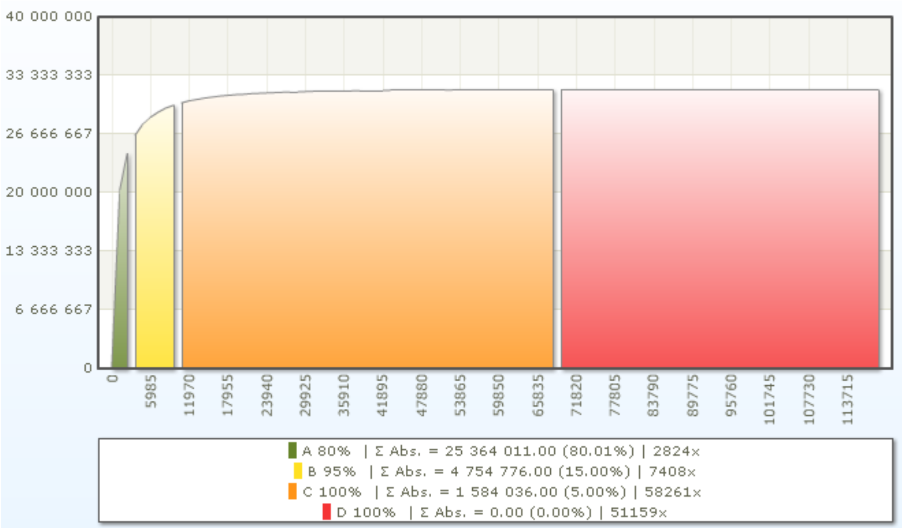

Figure 2: ABC analysis of spare parts inventory based on consumed quantity [pcs]. Dominance of categories C and D (i.e. items with very low or zero consumption) is characteristic for spare parts.

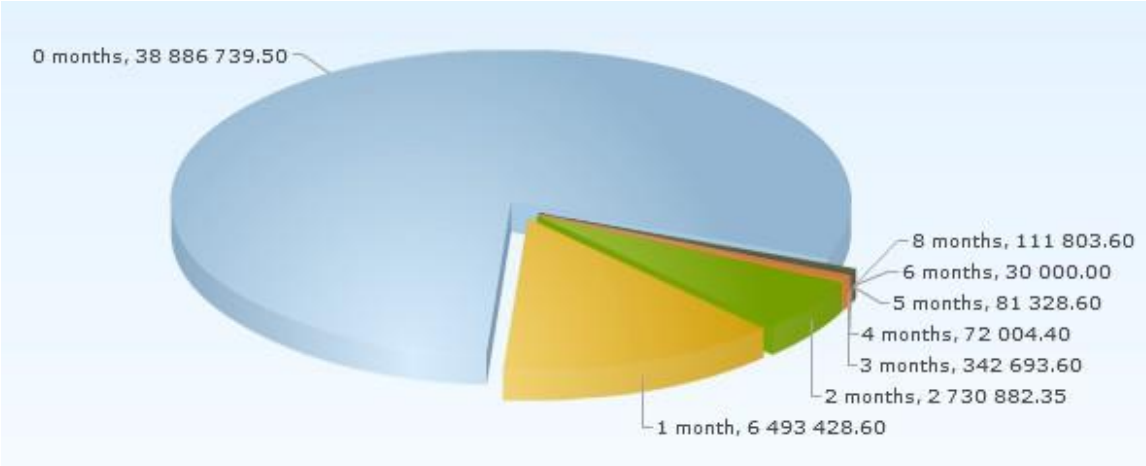

Figure 3: Spare parts inventory segmentation in value according to the consumption frequency in the last 12 months. Segment 0 represents the value of items with no consumption over the last 12 months; segment 1 represents the value of items with consumption recorded in 1 out of 12 months of the analyzed year, etc.

Analyze spare parts criticality

In large organizations operating large production systems, the size of spares portfolio amounts to tens or hundreds of thousands of items. It is therefore essential to be able to distinguish the important ones from the others. Criticality of spare parts is after all the ultimate measure of spare parts' importance.

The level of a spare part's criticality is inevitably related to the criticality of the production equipment it is used for (so having an RCM analysis done will certainly help in assessing the criticality of spares). However, we need to keep in mind that criticality of spare parts is not equal to criticality of the device the spares are used for.

When analyzing criticality, we need to collect and look at various areas of data linked with the item: cost of inventory holding, failure probability, impacts of spare part unavailability, leadtime and other parameters – as shown in Fig. 4. Based on the level of item's criticality, appropriate service level targets should be set.

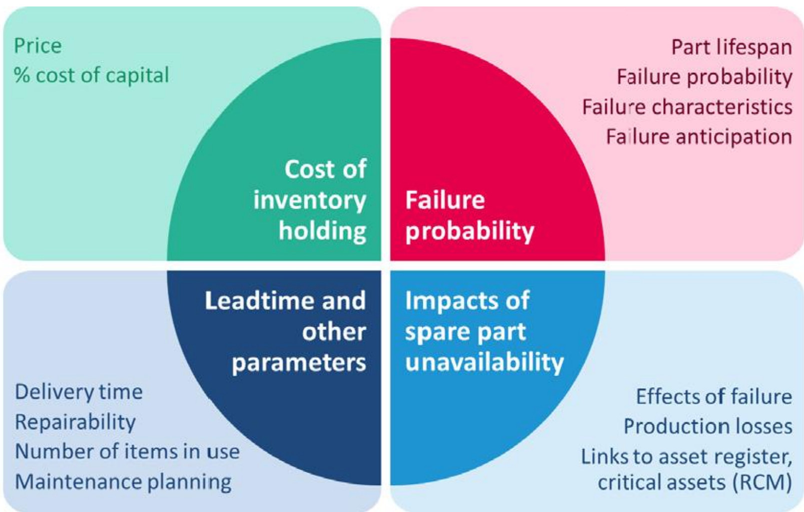

Figure 4: Spare parts criticality analysis areas

In practice, costs of inventory holding and costs of spare parts unavailability should be carefully balanced. Costs can be compared using the following equation:
(1)
Where Cinv are costs of inventory holding per one year and Cun are costs of unavailability of spare part in case of need calculated per one day. LT is lead time calculated in days and f is frequency or probability of failure (need for spare part) as occurences per year.

$$C_{inv} = C_{un} * LT * f$$

Figure 5: Equation of criticality calculation – example

If all data for the equation is available, criticallity can be calculated directly – and easily. But in practice typically some the variables in the equation are not known at all or are uncertain, blurred and inaccurate. This is where advanced analysis of avialable data comes to question. From our experience, in industrial organizations a number of interesting sets of data can be utilized to evaluate (or support evaluaton) of spare parts' importance (criticalness or criticality).
In the following diagram (Figure 6), a 2-level evaluation of criticality (or identification of critical items – materials or spare parts) is described. This 2-level approach allows for "clever", efficient process of evaluation of large numbers of items. Using various data sources like spare parts master data, history of spare parts transactions, RCM data, data from previous assessments of critical items, bills of materials etc., a preliminary separation of clearly non-critical items vs. suspicious (potentially critical) items can be done by means of data analysis without human interaction. After this preliminary evaluation, we can spot the relatively small group of potentially critical items and focus further evaluation on them. In this way the preliminary evaluation can safe a lot of work and time otherwise required from maintenance technicians to assess each item individually.
In the second step, potentially critical items are scrutinized thoroughly to find out their level (score) of criticalness. This can be done either in quantitative way (if required data is available) or qualitative way (data must be collected by means of questionnaires filled-in by maintenance technicians or engineers).

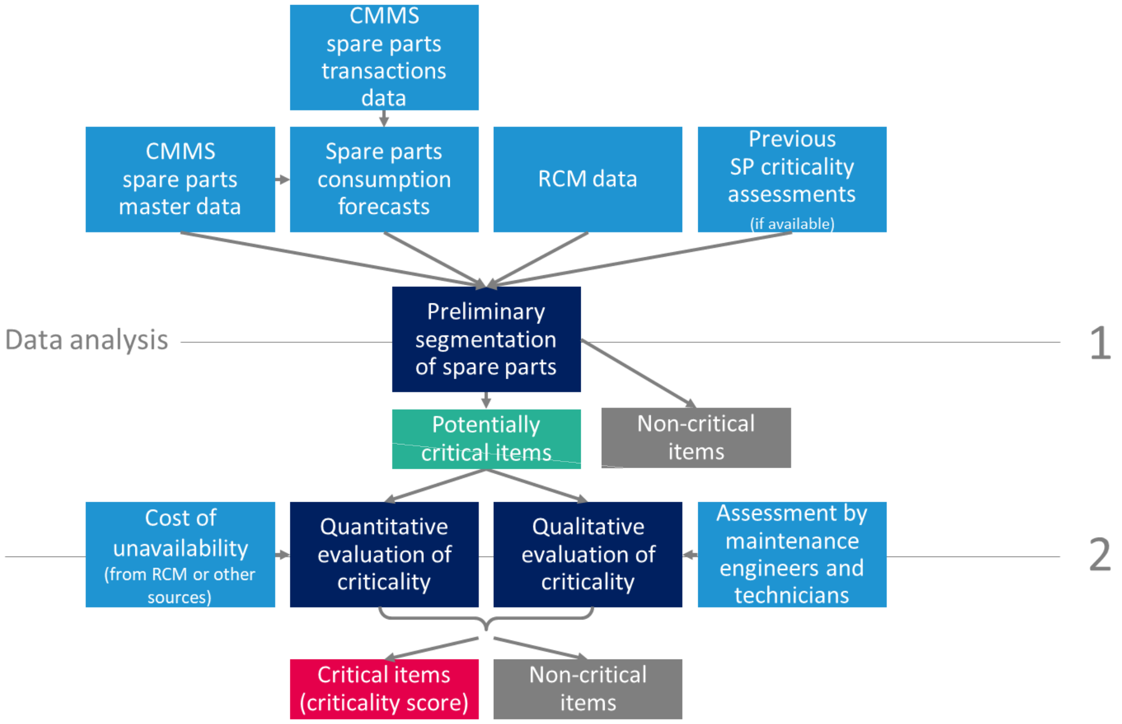

Figure 6: 2-level evaluation of spare parts criticality.

If data for quantitative calculation is not available, we need to rely on information from maintenance engineers or technicians. To objectivize their subjective view on spare parts (maintenance engineers are often strongly biased towards keeping excessive inventory, "just to be safe"), we have proposed a structured questionnaire. Questions about spare parts relailability, probability of failure, and impact of unavailability, lead time, etc. should be designed to fit specific conditions of the organization (industry, technology/production equipment used etc.). The equation (1) should be taken into logarithm, so we can change variables for indices which can be added and subtracted instead of multiplicated. Answers should be given weights, and the questionnaire should be balanced so that we can have sums for each area (index) as shown in the following equation:

$I_P-I_{un}-I_{LT}-I_f=0$ (2)

This allows for summing weights for answers in each area into a single index. If the left side of equation is greater than 0, we should keep at least one item of spare part in stock. If it is less than 0 we should not – this spare part is not critical.

Weights should be tested on selected parts with known (or agreed) criticallity. A pilot mix of spare parts should include some parts which are critical for sure, some which are not, and some which are in between.

It is essential to include maintenance engineers in both selecting questions for the questionnaire and in selecting weights for answers. This helps to create a better understanding of the questions and the whole purpose of the criticality assesment. A maintenance engineer should be able to fill the questionnaire in an average time of 2-10 minutes, so that the criticallity assesment will not consume much of working time.

Although assessment can be done on paper or in Excel, today it makes great sense to use available services like Google Forms or SurveyMonkey or others, that can be used to collect needed data and minimize the work with collecting, processing and analyzing the data.

Spare parts management starts with good forecasting

The next step in the specification of optimum spare parts inventory management regime is the prediction of future demand (consumption) for the items in stock. The forecast is always based on transactional data from information systems – history of spare parts consumptions, which must be representative (meaning sufficiently long). In the case of spare parts, we usually work with a history of three to ten years (depending on industry). Three years of recorded history seems to be the minimum for intermittent items. A general rule here applies: the longer the history, the better and more reliable the forecast.

When analyzing historical consumption, we need to carefully distinguish between material consumed for planned maintenance (planned shutdowns, turnarounds, preventive maintenance) and spare parts issued for unplanned (corrective) maintenance – repairs. In forecasting, we must adjust the history for planned maintenance.

In the forecasting process, items should be treated individually, according to the character of their consumption. Items with common demand patterns (high runners – fast moving items like fasteners, etc.) can be forecast using a number of standard statistical methods normally used in inventory management (moving average, exponential smoothing, Holt's exponential smoothing, trends, seasonal indexes, Winter's method, etc.). Items with intermittent demand require a special suitable method to be applied. The use of standard methods of prediction and inventory management in case of intermittent items results often in a substantial overestimate of future consumption and therefore excessive inventory level.

Intermittent demand is the pitfall of spare parts management

One of the specific problems in spare parts inventory management is the nature of spare parts consumption - intermittent demand. If we analyze the consumption history of a typical spare part, we find that the historical consumption in most of the analyzed periods amounted to zero. Such infrequent or intermittent demand, usually with demanded quantity of just a few pieces, is very typical for spare parts and other maintenance inventories. An example of the consumption history of an intermittent demand item is presented in Fig. 9.

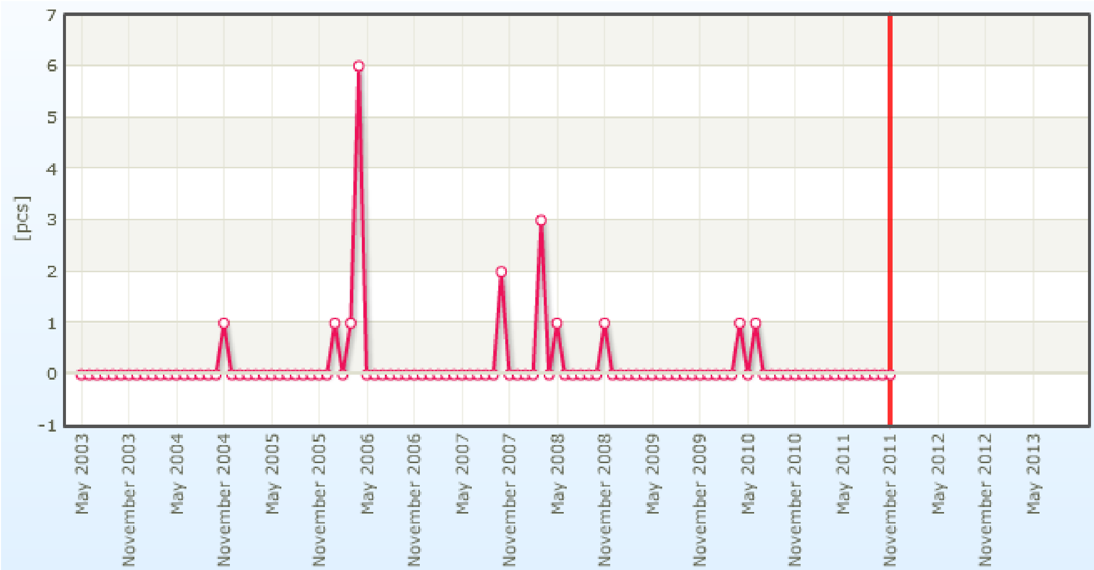

Figure 7: Intermittent demand in maintenance (item: Spiral sealing DN25-40 RF)

In maintenance, intermittent demand is quite often combined with long supplier leadtimes. For maintenance inventory management, intermittent demand and long leadtimes are a tricky complication, often leading to large overstock. The main problem with managing and forecasting intermittent items is that the standard forecasting methods used for fast moving goods (for instance moving averages, exponential smoothing, Holt's and Winter's method, constant or regression models with seasonal indexes, etc.) simply do not seem to work for these items. In case of intermittent consumption, special statistical methods (such as bootstrapping or Smart-Willemain method) need to be applied.

Smart and Willemain (2004) suggested a stochastic simulation forecasting method. Using this method it is possible to specify minimum inventory level (re-order level) in order to ensure fulfilment of requirements with target probability (logistic service level, target of availability). The method is based on random sampling from the history of consumption. In statistics, similar methods are called bootstrapping.

Besides intermittent items, in a large maintenance inventory we can also find fast-moving items with stable and high regular consumption. These are especially items of common consumables like fasteners, generic gaskets, or bearings. For these items, standard methods of inventory management and future demand forecasting can be applied.

Identification of spare parts and cleaning master data

In spare parts optimization projects we quite often face various problems with quality of spare parts master data – especially naming: issues with unstandardized naming or incorrect names, names in various languages, different word order, typos etc. hinder significantly all efforts in spare parts optimization and generally result in duplicate (or multiplicate) master data records for identical materials (identical spare part is stored in several master data records with different names). In order to clean spare parts master data we apply advanced data analytics on master data to identify or cluster duplicate (or similar) items. This key analytical method

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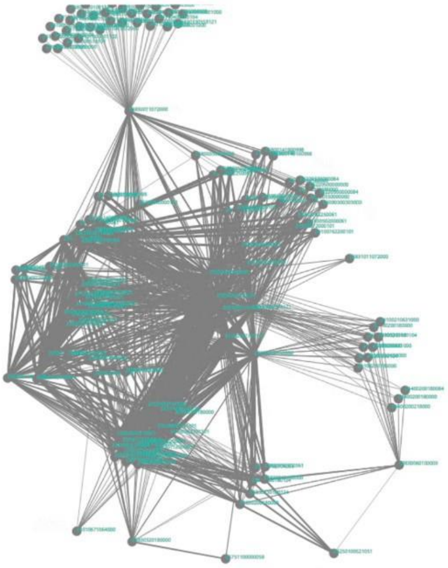

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23830491708121		23830330518000		99,4 %
23830491708121		23830330559121		99,4 %
23830491708121		24400450100000		99,3 %
Total				**88,2 %**

Figure 8: Clusters of similar items found in master data.

	A	B	C	D	E	F	G
149	sapId	czName	czN16	(178) Jmenovitý tlak / Tlaková třída	(181) Materiál	(125) Tloušťka (mm)	(175) Velikost (jm
150	**L00176**	**Čočka průchozí 12020 PN325 DN90**	**Těsnící VT čočka DN90 12020 N16.501**	**PN325**	**12020**	**25**	**DN90**
151	105676	Čočka průchozí 12020.1 PN325 DN90	Těsnící VT čočka DN90 12020.1 N16.501	PN325	12020.1	25	DN90
152							
153							
154	sapId	czName	czN16	(178) Jmenovitý tlak / Tlaková třída	(181) Materiál	(125) Tloušťka (mm)	(175) Velikost (jm
155	**L00172**	**Čočka průchozí 12020 PN325 DN200**	**Těsnící VT čočka DN200 12020 N16.501**	**PN325**	**12020**	**40**	**DN200**
156	105354	Čočka průchozí 12020.1 PN325 DN200 Atyp	Těsnící VT čočka DN200 12020.1 N16.501	PN325	12020.1	40	DN200
157							
158							
159	sapId	czName	czN16	(178) Jmenovitý tlak / Tlaková třída	(181) Materiál	(125) Tloušťka (mm)	(175) Velikost (jm
160	**L00169**	**Čočka průchozí 15412 PN325 DN250**	**Těsnící VT čočka DN250 15412 N16.680**	**PN325**	**15412**	**52**	**DN250**
161	105351	Čočka průchozí 15412 PN325 DN250	Těsnící VT čočka DN250 15412 N16.680	PN325	15412	50	DN250
162	105581	Čočka průchozí 15412 PN325 DN250	Těsnící VT čočka DN250 15412 N16.680	PN325	15412	50	DN250
163							
164							
165	sapId	czName	czN16	(178) Jmenovitý tlak / Tlaková třída	(181) Materiál	(125) Tloušťka (mm)	(175) Velikost (jm
166	**L00168**	**Čočka průchozí 15412 PN325 DN250**	**Těsnící VT čočka DN250 15412 N16.680**	**PN325**	**15412**	**46**	**DN250**

Figure 9: Validation table with potentially duplicate items found in master data.

Conclusions

It can be concluded that spare parts management as a part of physical asset management has significant impact on financial statement of the company. Good spare parts management brings the following benefits:

Optimum spare parts quantities are purchased
Optimal purchasing cashflow
Lower inventories
Less unused inventories
Higher availability of needed spare parts
Good risk management

Various sets of data can be used to support or optimize spare parts management, especially in spare parts segmentation, criticality assessment, forecasting, master data rectification. The examples demonstrated in the paper indicate ways to utilize vast amounts of data available in organizations today – to actually monetize the data by improving efficiency and effectiveness of spare parts management processes.

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Effects of Using Big Data Methods on Optimizing Electrical Systems

ID 132

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Abstract

Electricity systems are the most crucial systems in our everyday life. Many researches has been made recently for developing new methods for energy conservation, and this has arisen more interest in optimizing this sector. Thus, our paper discusses the implementation of big data methodologies in dealing with power and energy. Big data methods include the extraction, transmission, processing, and analyzing the data from a certain data source. In our case, we suppose that the data sources are electrical components in the electricity systems. However, the use of big data will optimize energy consumption, reduce risks and help decision makers to take the right decisions by monitoring their systems constantly. In this paper we compare between the current situation and the best practice in energy optimization field. We also show how big data approaches reduce the gap between them.

Keywords: Big Data, Optimizing electrical systems, Smart buildings.

Introduction

Over the past few years energy consumption and optimization formed a huge challenge in the fields of operation and maintenance, while the dependency on electrical power increased for various applications the lack of feedback and information increased the possibility of energy loss. This increase in electrical power demand is seen in the international energy agency findings [1] that in the year 2018 the global energy demand increased by 2.3%, also the same agency shows that electrical energy waste is on the rise as the following quote states “The International Energy Agency also recently released a report estimating the amount of energy wasted by standby products each year to be between 200 and 400 terawatt hours. In comparison, the entire country of Italy consumes 300 terawatt hours of energy each year” [2]. While many applications have been introduced in the past to overcome this issue, the problem is yet to be resolved.

In 2010 a paper titled “Scoping the potential of monitoring and control technologies to reduce energy use in homes” [3] stated that 39% of the residential energy was wasted, such findings are evidence of the urge to come up with a solution to such problem. Another paper titled “Smart building energy management based on network occupancy sensing” [4] introduced a solution to the problem mentioned above using BEMS concept with multiple sensors that gather data, this project concluded with impressive results of reducing the total energy consumption in buildings by 10.22%

each day.

Another important aspect regarding this issue that the paper will cover is the importance of big data in optimizing energy consumption, since data collection and feedback can provide decision makers of different levels with enough information to deal with energy consumption in both active and proactive manners that can lead to better efficiency. The challenge of implementing such system is the lack of information which is due to the incapability of extracting data from the existing devices. This challenge introduced the need of having a comprehensive system that can utilize extracting and analyzing big data in optimizing the energy consumption in different applications.

This paper will discuss this problem starting with a brief background regarding energy consumption and energy monitoring including the lack of a comprehensive system that can collect data and control units in buildings, another important note to be discussed in this paper is the best practices and the international standards regarding energy, followed by the proposed solution, challenges of such design are also discussed in this paper.

Background

Conventional Methods

One of the current solutions for the problem stated in this paper is the BEMS (Building Energy Management Systems), this system depends on having a high tech sensors located in the infrastructure of the building that are connected to a central control unit responsible for both monitor and control of the appliances in the facility, the IEA (International Energy Association) describe BEMS as "an electrical control and monitoring system that has the ability to control monitoring points and an operator terminal. The system can have attributes from all facets of building control and management functions such as heating, ventilation and air conditioning (HVAC) to lighting, fire alarm system, security, maintenance, and energy management." The system work flow is illustrated in figure (2.1) below.

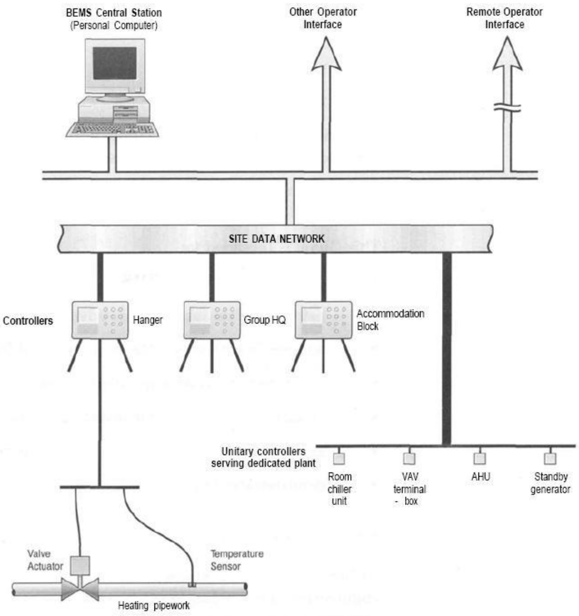


Figure 1 BEMS model.

The BEMS does indeed increase the efficiency in energy consumption by monitoring and applying certain actions like controlling HVAC (heating, ventilation and air conditioning) systems and lighting, but it also has a lot of disadvantages such as:
Having high initial and operational cost
It needs trained personnel to operate the system.
To achieve the goals of the system, it always needs the attention of the operator.
There are many solutions proposed like BEMS and EMS to the problem stated in this paper, but the lack of utilizing the data gathered and the lack of the ability of gathering information from devices is what these systems have in common, this disadvantage along with high initial cost and complicated operation procedure reduce these systems efficiency.

Human behavior using electricity
One of the major causes of the problem discussed previously is the way humans interact with electricity, there are many misconceptions regarding the uses of electricity in the crowd minds such as that devices connected to the grid (by plugs or otherwise) do not consume electricity while in the contrary a huge portion of the generated power is wasted each year by these kind of devices and behaviors, in California alone the California Energy Department estimates that charging devices kept plugged in to the grid waste around 60% of the power delivered to it which is equivalent to the amount needed to power 350,000 homes.
Humans are not only the ones to blame for such a waste, the lack of instantaneous feedback and appropriate alarms keep humans unaware of the energy waste around them, this led to huge increase in the electricity bell for unnecessary reasons, in United States power consumed from unused devices costs around $3 billion each year.

Another important aspect is the impact of such waste on the environment, the generation of electricity is one of the major sources for greenhouse gases, as the United States Energy Protection Agency released, in 2017, and electricity generation produced 28% of the total greenhouse emissions being the second source after transportation.

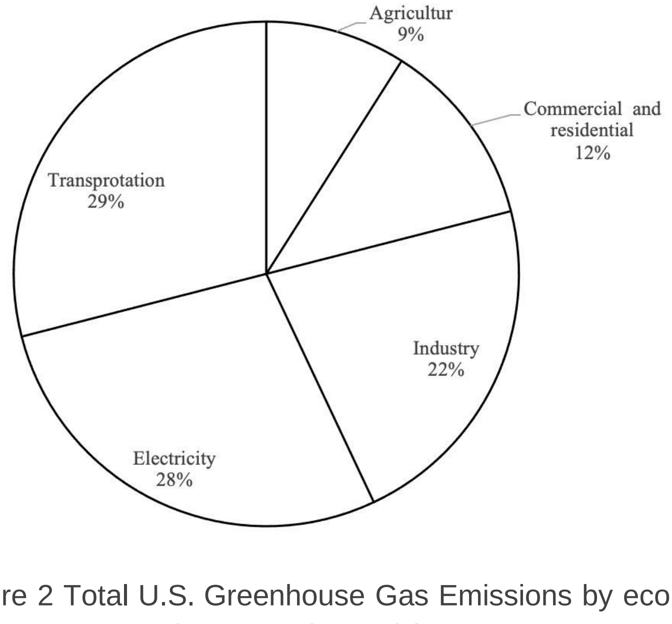


Figure 2 Total U.S. Greenhouse Gas Emissions by economic sector in 2017

If we examine the electricity sector itself and based on the information provided by United States Energy Protection Agency, the residential and commercial sectors form 61% of the total greenhouse emissions produced by electricity generation.

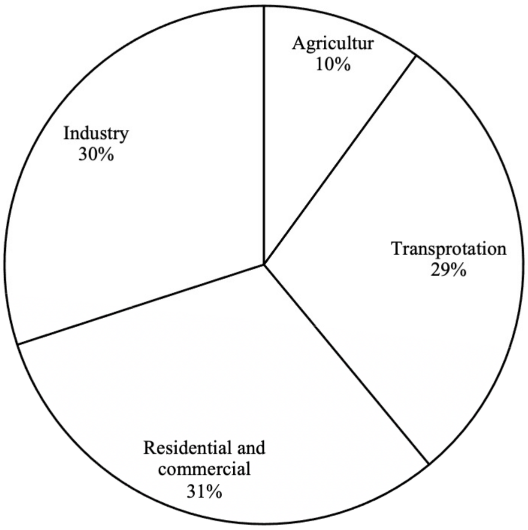


Figure 3 Total U.S. Greenhouse gas Emissions by sector with electricity distributed

It is noted that aiming for a better efficiency in electricity consumption is one of the best solutions regarding the huge waste humans make, this can be seen by one of the recommendations the Energy Protection Agency stated on their website " Increased End-Use Energy Efficiency through reducing electricity use and peak demand by increasing efficiency and conservation in homes, businesses, and industry, EPA's ENERGY STAR® partners removed over 290 million metric tons of greenhouse gases in 2017 alone, and helped Americans save over $30 billion in energy costs, approximately 370 billion kWh of electricity."

Risk factors

Energy monitoring and controlling does not only increase the efficiency of power consumption, but it also increases the safety of humans in the first place followed by materialistic objects such as machines and facilities.

There are many risks facing electric devices such as power outages and power surges. Power surges can be caused due to the high demand of devices from the shared power supply, this can increase the voltage thus damaging devices, these faults cost resources and time and can be prevented by monitoring the grid and predicting such faults before it happens.

Best Practice

Energy reduction practices fall into two major categories:

Supply-side management: Replacing conventional energy with clean, renewable energy technologies.

Demand-side management: Using tactics to reduce the need for energy through system-wide energy conservation and to reduce the cost of maintaining such a system.

International Standards

Interoperability is defined as the capability of two or more networks, systems, devices, applications, or components to share and readily use information securely and effectively with little or no inconvenience to the user.

If there are no standards, systems will lack interoperability. To standardize the systems' protocols and communication techniques, an Information models should be developed, or use an existing information models such as IEC 61850 used to communicate with MDMS and related enterprise applications. Recently, advanced protocols are required, so a new information model has been published as IEC 61850-90-7.

Risk management

Risk management is the identification, evaluation, and prioritization of risks (defined in ISO 31000 as the effect of uncertainty on objectives).

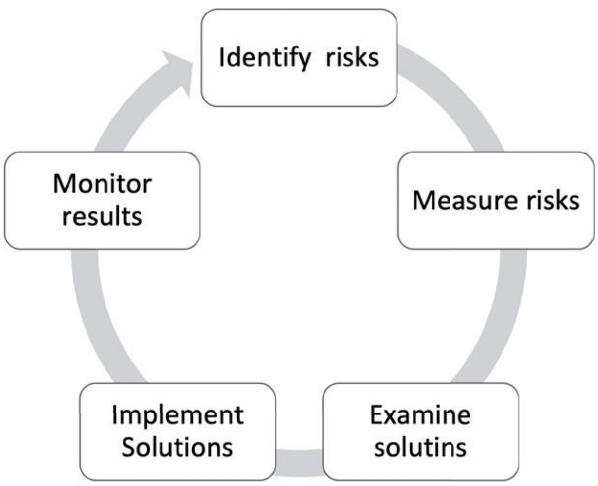
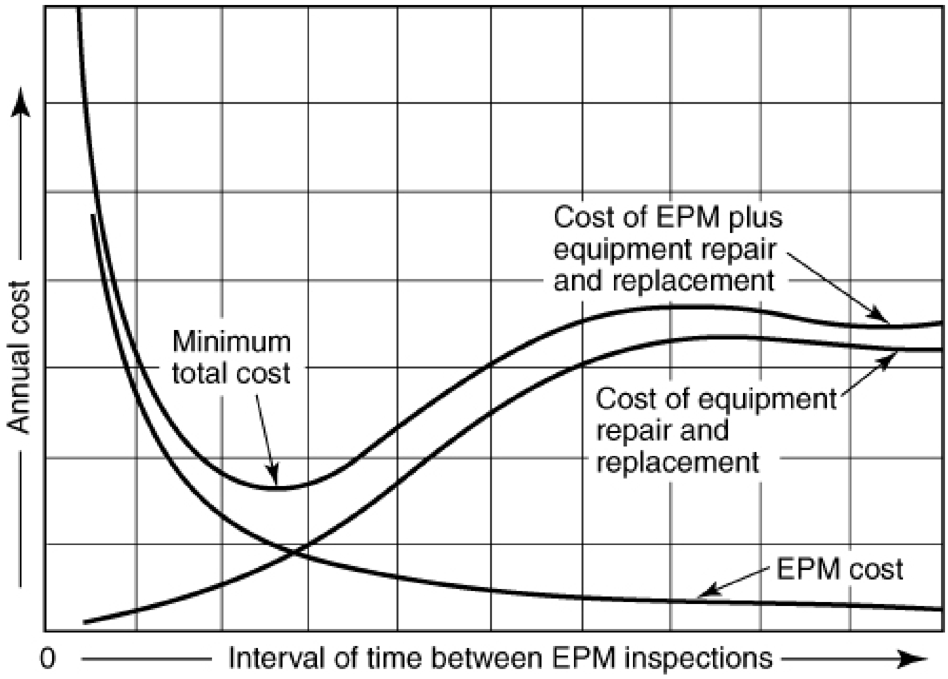


Figure 4 steps of risk management

Once risks have been identified and assessed, all techniques to manage the risk fall into one or more of these four major categories:
Avoidance (eliminate, withdraw from or not become involved).
Reduction (optimize – mitigate)
Sharing (transfer – outsource or insure)
Retention (accept and budget)

Risk avoidance is not to perform an activity that could hold a risk; meanwhile, Risk reduction is reducing the amount of the loss or the possibility of the loss occurring; Risk sharing could be considered as sharing part of the loss or the gain with another party, from a risk, and the measures to reduce a risk; Risk retention involves accepting the loss, or benefit of gain, from a risk when the incident occurs.
Having a comprehensive big data model that records the parameters of used appliances in a certain facility can be beneficial in predicting future failures, thus, risks could be solved faster and easily contained or planed for.
Preventive maintenance
Preventive maintenance is regular, planned maintenance that is scheduled according to usage or time-based triggers. The cost of preventive maintenance will reduce the cost of breakdown repairs. An effective preventive maintenance program holds the sum of these two expenditures to a minimum.



EPM programs play a key role in energy conservation, saving money and vital resources. Appliances that are well maintained work more efficiently and uses less energy.

Big data as a solution

According to Oxford's definition of the term: "big data is extremely large data sets that may be analyzed computationally to reveal patterns, trends, and associations, especially relating to human behavior and interactions" [5]. We can apply this concept by extracting large amount of data from electrical systems by monitoring different system states at different times. Patterns and trends can be extracted from the behavior of users toward power utilization. A great example of such users are people living in their houses, they interact with most of household machines with a certain routine, while each house has its own routine. The most convenient solution is to make the electrical system learn its users' routine in order to be optimized. For the system to get trained on such a routine it detects a pattern of similar data inputs over time, and this is the concept of big data.

There are many benefits of using big data analysis in power systems in all stages including power generation, distribution, and consumption stages. In this paper we mostly focus on the power consumption stage, because this stage is the most crucial as it influences the decisions needed in the other stages.

Sensors and smart meters are used to extract the data from electricity systems. Sensors may be attached to the existing power lines (fig 4.1.b and fig 4.1.c) communicate data with the central processing system. Fig 4.1.a shows a traditional electrical system while fig 4.1.b shows the data extraction elements, and usually after data is extracted and processed, the system takes a decision to make an action through an actuator as in fig 4.1.c. However, data can be extracted on different levels; district level, building levels, room level, device level, or multiple levels combined together. Real time data extraction from electric power systems can allow the systems to monitor power dissipation, voltage and current levels at real time as well.

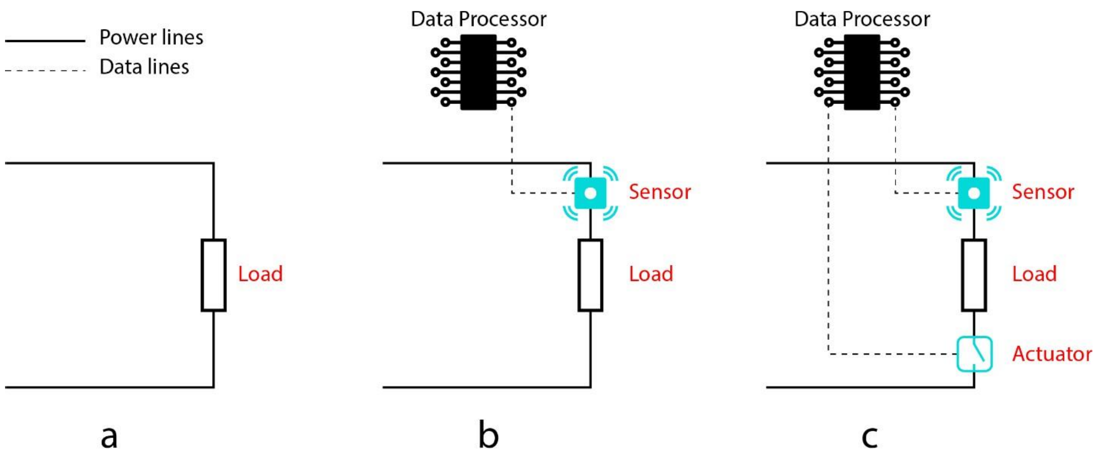


Figure 6 Extracting Data from Electrical Systems

The load represented in Fig 4.1 can denote a simple light bulb as well as it can denote a data center on the electricity grid. The implementation of big data extraction are very diverse but they are similar in concept.

Categorizing User Benefits

The benefits of analyzing the big data which might be extracted out of an electricity system can be divided into 3 categories depending on the level of interaction with the system:

Industries and individuals

This user group will mostly benefit from interactive systems that integrate big data management by monitoring their electrical activities. From facility managers to normal residents, this will help optimizing their expenses by reducing the unwanted power dissipation, either manually by themselves or automatically by letting the interactive big data system to manage their power dissipation. These systems exploit big data to be used in decision making in order to control electrical appliances by switching them on or off.

Using big data applications in electrical systems, individuals can have full insight about their consumption and their spending rates. In contrary with traditional systems, users can have real time energy monitoring at any time instead of one report monthly.

Governments

Big data can help governments or their agencies to enhance their electricity distribution grids. The benefit of the big data in this category is the ability to extract reports periodically for the electrical grid load distribution by area, or by generating heat maps that can be beneficial for taking the right decisions. With good availability of data sources, big data management models can generate as much and as little details as needed.

System developers

Big data system developers are agencies and corporations who work on the implementation of a comprehensive system to monitor and manage power consumption. This class can also use the generated big data in order to modify their own systems. The generated data may include the time stamps of failures happened within the system, time stamps of idle states in the system, or a gap in the data format that needs to be fixed. System developers may use machine learning methods in order to make the system more intelligent and capable of optimizing energy consumption based on user behavior.

Risk Reduction Using Big Data

As mentioned before, risk management has been standardized and categorized into four categories. The integration of big data within electrical systems can assess in reducing the risk in several categories of risk management.

Security and fraud detection

Governments can integrate data generating nodes to track the flow of the electricity in the grid. By tracking the flow, they can make sure that the consumed amount is the same as the recorded amount by power meters readings. They can track loopholes in the grid and prevent fraud if there was any.

Power outages

One of the major risks in electrical systems is power outages. According to the American Meteorological Society, big data provide the ability to predict the outages that may happen in the electricity grid which can help the electricity providers to avoid or reduce the time of the outage [6]. This can also avoid the risk in facilities if the system send alerts to decision makers warning them about a possible outage and its timing.

Big data with machine learning

Big data extraction is usually associated with machine learning. Since it is very difficult for humans to extract patterns and trends from a very big bulk of data manually, computer scientists tend to use machine learning methods instead. Thus, electrical systems data is a good raw material for machine learning since machine learning can analyze the power signals in the electrical devices and notice any abnormality in these devices. It is expected that machine learning can predict failures within electrical devices before the failure is irreversible. This can be done if the dataset used to feed the machine learning algorithm was good fit for its purpose.

Challenges

Using the big data models in electricity systems is a convenient solution that reduces the gap between the best practice and the current situation. On the other hand, using big data is still facing several challenge that are going to be mentioned in this section.

Storage

Big data by its name allocate big memories and servers. The challenge is to maintain this huge information in one place and keep it accessible at all times.

Data structure/format

Although most of the sensors and devices in electrical systems are interoperable, the lack of a standardized data format for all systems is still a challenge. In some cases an intermediate data conditioning stage has to be developed in order to normalize all the data to fit one data structure.

Data Governing

As the electricity sector is usually considered a sensitive sector. Researchers and developers of such systems do not have their full freedom to implement their solutions on a very wide range. Data privacy is also a big issue in this industry as it deals with people’s behavior sometimes.

Computational Power

Computational power is very crucial when dealing with big data applications. If the solution is a real time monitoring system, it needs a huge computational power that must be capable of processing big amount of data.

Information Security

Like any other topic in the ICT field, cyber security is a constantly rising concern. As a solution a solution that uses big data, data must not be exposed to any type of attacks. To secure the huge amount of data, big efforts are needed.

Conclusion

Energy consumption and optimization is a huge challenge in operation and maintenance, the conventional solution for such a challenge needs a high initial cost, trained personals, and it's a semi-automatic operation. Using a big data model integrated with a standardized systems would drastically reduce the initial cost and the need of a trained personal, on the other hand it would make such a system more self-dependent and self-developed.

Using such a system in buildings or projects would reduce the running cost, thus reducing the total cost of ownership.

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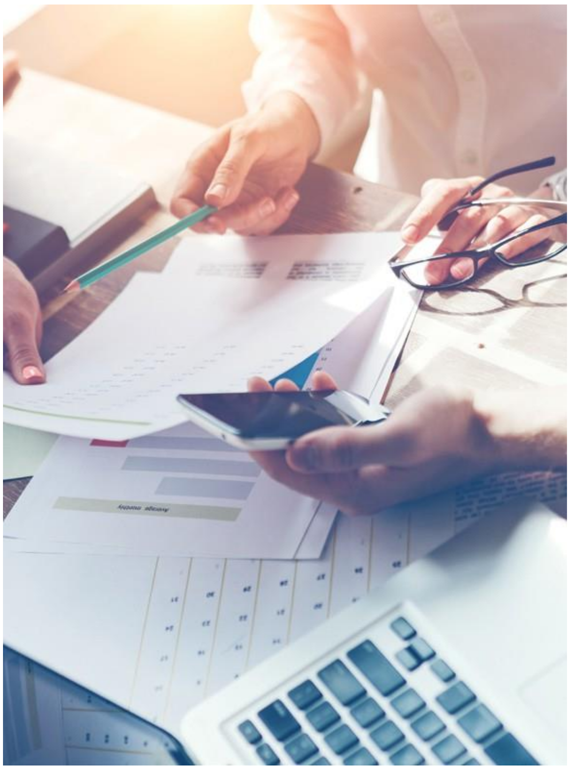

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