# Intelligent Maintenance of Large-scale Belt Conveyor Idler Rolls: State-of-the-art and Opportunities

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## ABSTRACT

Large-scale belt conveyor systems are widely involved in medium and long distance transport of bulk material. The spatially distributed idler rolls are a great challenge to maintain the reliability of the conveyor systems. Automation of maintenance in intelligent ways provides a promising solution to replace traditional corrective maintenance. This paper further elaborates the concept of intelligent maintenance introduced by Lodewijks in 2004. We review state-of-the-art idler roll data acquisition, decision-making techniques and recent development of robotic roll replacement. A novel SD model based maintenance logistics control is proposed. The viability of robotic idler roll replacement has been demonstrated by case studies. Opportunities in the intelligent maintenance of idler rolls are discussed. Cloud-based intelligent maintenance is considered an emerging trend in the near future.

Keywords: belt conveyor; idler roll; intelligent maintenance; condition monitoring; decision-making; robot;

## 1    INTRODUCTION

Large-scale belt conveyor systems are widely applied in continuous bulk material transport, for instance mines, terminals and power plants [1]. The reliable performance of the belt conveyor system is crucial since downtime leads to production loss. Maintenance activities play an important role in enhancing the long-term reliable performance. Especially, the industry are facing with a great challenge to effectively maintain tens of thousands of idler rolls within a typical large-scale belt conveyor. The number of idler rolls easily reaches more than 2000 per kilometer and considering the effects of the catastrophic failure (belt rip etc.) possibly caused by failed rolls, special attention needs to be put on idler roll maintenance. Existing maintenance executions on idler rolls are still labor intensive, time consuming and requires the system to stop running otherwise it is too dangerous for maintenance personnel.

In order to represent the condition of an entire belt conveyor system, an Intelligent Belt Conveyor Monitoring and Control (IBCMC) system was developed at the section of Transport Engineering and Logistics of Delft University of Technology (TEL) [2], by which the interrelationship among monitored components can be investigated so that maintenance and operational strategies can be chosen to achieve optimum system goal. As one of crucial agents of IBCMC, the Intelligent Maintenance of Idler Rolls (IMIR) needs to be further investigated in order to provide accurate and complete local decisions for IBCMC.

In 2004, Lodewijks proposed the concept of intelligent maintenance of large-scale belt conveyor idler rolls [3]. Intelligent maintenance was defined as automated maintenance that has the ability to make decisions based on monitoring information or provided by the central control system. The realization of the intelligent maintenance system with different components like a powered trolley and condition monitoring was discussed. Since then, intelligent maintenance has been inspired for further scientific research and industrial tests. In order to lower the cost of production in the long term, new automation technologies and intelligent decision-making are literally introduced into the conveyor industry.

Since idler roll load calculation models were not precise enough, the logistics simulation model developed by Lodewijks was based on either statistic lifetime data provided by bearing manufacturers, or based on real-time monitoring data and analysis. The drawback of the simulation model based on statistic data is that it does not include the actual utilization of the conveyor system. This generally leads to an imprecise prediction of lifetime of idler roll, resulting in too early or too late roll

replacement. A rigorous idler roll load calculation model, Stress Discontinuity model (SD model), was recently developed at TEL by Liu et al. [4]. With this model, the expected lifetime of idler rolls can be calculated according to the cumulative capacity diagram of the conveyor. This model can largely improve IMIR by providing precise residual life of idler rolls.

As an independent yet connected part of IBCMC, IMIR is designed to fulfill all kinds of functions, such as self-driven, positioning, and monitoring. The architecture of IMIR can be seen in Fig. 1.
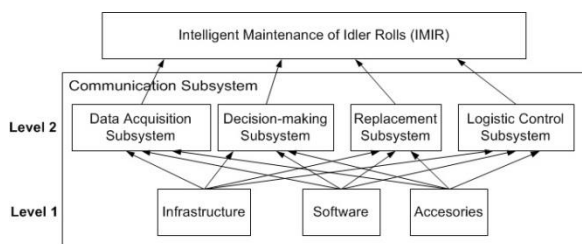


Fig. 1 Architecture of intelligent maintenance

- Level 1

  Level 1 is the component level. Three categories of components can be distinguished for each subsystems in Level 2, Infrastructure, Software and Accessories. Infrastructure mainly consists of all kinds of civil constructions and/or hardware, for instance the rail track or road. Obviously, Software is the program that fulfil the required functions of each subsystem. All others belong to Accessories.

- Level 2

  Level 2 is the subsystem level. In IMIR, there are four subsystems, namely Data Acquisition Subsystem (DAS), Decision-making Subsystem (DS), Replacement Subsystem (RS) and Logistic Control Subsystem (LCS). Each subsystem will de elaborated in details in following sections.

- Communication Subsystem

  It includes not only the communication between IMIR and IBCMC, but the information transferring among different subsystems. Currently, wireless communication solutions seem to be promising, for instance RFID technology [5], [6].

## 2  DATA ACQUISITION SUBSYSTEM

Traditionally, the inspection of idler rolls relies on human perception through watching or listening 'walking along the conveyor'. The limitations of 'walking along the conveyor' maintenance have been widely recognized, for example delayed failure detection, the high cost, intensive labour activities and dangers [7]. In recent several years, automated sensing techniques for DAS have been largely improved.

### 2.1  SENSORS

According to the physical position and layout, monitoring sensors can be categorised into mobile sensors and fixed sensors. Mobile sensors can be installed on the arm of a robot, or an outstretching arm of the maintenance carriage/trolley. The mobility of the mobile sensors can largely lower the complexity of the sensor infrastructure and network. The disadvantage of the mobile sensor, however, is that the monitoring circle can be much longer than with fixed sensors.

On the other hand, fixed sensors usually are installed either inside the rolls, or attached to the support frame. In order to obtain reliable signal to represent the condition of the bearing inside the roll, a principle of thumb is to locate the sensor internally close to the bearing. When looking at the design of current sealing, one can find a promising solution is to integrate the sensor into the sealing. Researchers at TEL has carried out a research project on development of 'Smart Idler', which is equipped with thermal sensors and an energy harvesting system [6]. Recently, An Australian company Vayeron Pty Ltd also announced their product of Smart-Idler [8]. The patented product consists of thermal, vibration and acoustic sensors together with RFID technology.

Fixed sensors which are installed onto the support frame mainly rely on the vibration or acoustic sensing techniques. Intium Solutions recently released their Roller Condition Monitoring (RCM) system, which consists of vibration sensors attached to the frame, a communication mechanism and a database [9]. Honeywell International Inc. patented their in-belt plug monitoring system [10]. With three sensors plugged into the bottom side of the belt, the sensors can perform pressure, vibration and/or temperature measurements during operation.

Compared to mobile sensors, a crucial drawback of fixed sensors is the power supply. Up to date, rolls integrated with self-power sensors still cannot be realized in large-scale

production. Energy harvesting techniques based on vibration or solar are still in infancy. Opportunities lie here in optimum design of the energy harvester which is suitable for large-scale production.

Thermal, vibration and acoustic sensors are most common in DAS of idler roll maintenance. Of the three physical variables, vibration is widely accepted in scientific community and industry for the reliable detection of premature defects of individual roll, but it requires post-processing. For thermal data acquisition, thermal to electrical sensor or thermal graphic scanning are commonly applied to detect the temperature or heat of the bearing houses. For acoustic measurement, ultrasonic technique normally is applied to distinguish bearing failures associated with inadequate lubrication and minor defects [11].

Where it is not a big issue to install the DAS for one idler roll in the laboratory environment to acquire reliable result, significant challenge lies in the installation of on-site data acquisition for groups of idler rolls. For thermal measurement, for instance, the condition of the bearings in center roll is rather difficult to detect due to limited space. For vibration and acoustic signal, it can also be easily interfered by neighboring rolls or vibration of the support structure.

## 2.2 DATA TRANSFER

Recent development of DAS focuses on wireless communication technologies and power harvesting.

As shown in Fig. 2, RFID technology is a promising solution to build a wireless network along the conveyor for the purpose of data transferring [5][6]. The combination of RFID tag and the temperature sensor enables continuous online monitoring of individual idler roll and real-time data transferring to the central control system.



*Fig. 2  RFID Node to node communication for conveyor idler monitoring* [6]

'Smart Idlers', which means idlers equipped with sensor nodes were researched at TEL

(Fig. 3). The 'Smart Idlers' are also equipped with self-power electromagnetic mechanism which can provide the energy for the sensors. Comprehensive studies have been carried out that it indicates the electromagnetic can be a promising solution for energy supply of sensors.
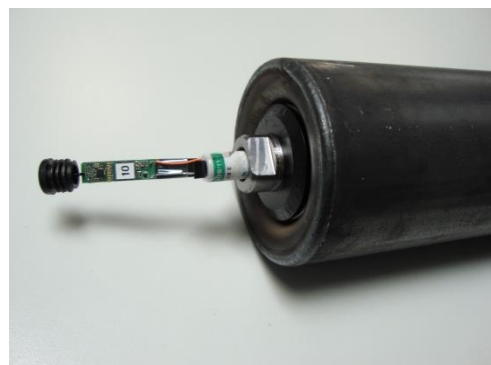


*Fig. 3  Prototype of 'Smart Idlers' at TU Delft RFID Laboratory* [6]

## 3  DECISION-MAKING SUBSYSTEM

The Decision-making Subsystem (DS) is known as the "coordinator" to subtract useful information hidden in the data from DAS, and give out decisions to RS. DS relies on the accuracy of available real-time monitoring data, the knowledge of the failure mechanism of the idler rolls, and decision-making techniques to make a sound judgment regarding the condition of inspected idler roll.

Fig. 4 illustrates the condition of an idler roll versus service time. Initially, the new idler roll works perfectly under healthy condition. After a certain service time, incipient failure occurs in the roll especially in the journal bearings. It can still continue the role until the final failure appears. The final failure means either stuck rotation of the roll, impermissible runout or unbalance. In reality, phenomena like dramatically increasing temperature, rotating resistance, vibration or noise can be observed from idler rolls with final failure. Such Idler rolls need to be replaced in time, otherwise they will turn into the catastrophic failure phase, in which destructive phenomenon would occur for instance causing fire, or cutting of the belt.
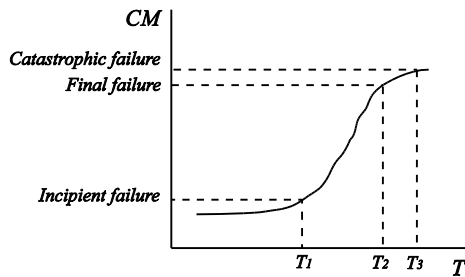
*Fig. 4 Idler condition monitoring versus time*

In order to investigate the failure mechanism of an idler roll, an on-site experimental study has been initialized at TEL. The aim of the experiment is to investigate the failure mechanism of idler rolls (Fig. 4) by applying multi sensors, and to build a knowledge base by which the IDS can be developed. Besides that, the feasibility of different types of signal (e.g. thermal, vibration and acoustic) for the on-site DAS will also be researched.

For the thermal measurement, which is either digital output of temperature or thermal/infrared image, a straight forward decision-making technique can be applied. High temperature normally indicates that the bearings are probably overheated due to wear or insufficient lubrication. Inspected rolls with overheat need to be replaced immediately, otherwise it may lead to fire. One crucial limittation of thermal/temperature monitoring is that it excludes the failure of the roll shell.

For DS based on vibration and acoustic measurement, data filtering and processing can be much more complicated and time consuming. Though vibration and acoustic monitoring of health of single roll have been proved to be reliable in laboratory environment, DS based on vibration and acoustic monitoring is still under discussion facing noises from neighbouring rolls, impact from lumps of bulk material and vibrations from the frame.

In order to achieve an efficient yet sound DS, Artificial Intelligence (AI) can be a promising technique. For instance, fuzzy logic was applied as belt conveyor inspection tools to determine the belt wear index and the conveyor inspection frequency index [12]. Other applications can be found in [13] and [14]. In addition, Pang intensively researched the development of knowledge-based systems [15][2]. Based on knowledge acquisition from gathered data and domain experts, knowledge-based systems provide DS formulated representation of reality and expert knowledge for reasoning and decision-making. The DS of IBCMC was studied thoroughly by Pang [2]. In

a typical DS, three fundamental functions can be distinguished, namely case retrieval, case completion and case adaptation.

## 4    REPLACEMENT SUBSYSTEM

With the development of robotic technology, the utilization of robots for the fulfillment of RS has come into reality.

Case 1 MAR Robotic Idler Changer

The MAR Robotic Idler Replacement System is capable of replacing individual roll on loaded, operational conveyors [16]. Installed on a truck workshop, the RS of the MAR system can automatically position the failed roll and exchange for a new one.

Case 2 Spidler

The Spidler (Fig. 5) is a carriage based automated roll replacement system, which is installed on light gauge rails mounted along existing conveyors [17]. The RS of the Spidler consists of a rotary table-mounted robot, which allows a wide range of motion to enable access to all rolls via either side of the conveyor. Laser scanners are employed to scan the idler rolls and frame dimensions prior to the exchange of the roll. The speed limit of the Spidler is 6 km/h.
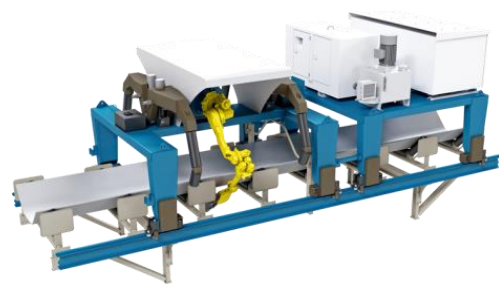


*Fig. 5 Spidler from Sandpit Innovation [17]*

From the above two successful cases of automated idler roll replacement systems, it can be concluded that the robotic technology is available for the specific application of RS in harsh working environment. One thing that needs to be mentioned is that the economic justification of an automated idler roll replacement system over traditional labor intensive replacement has not been carried out yet [18]. Parameters that can influence the Return On Investment are among others, the initial capital expenditure, installation cost, maintenance cost, downtime cost, safety and warranty.

# 5    SD MODEL BASED LOGISTIC CONTROL SUBSYSTEM

In [3], the LCS was determined by applying a logistics simulation model. The model took into account both the parameters of the conveyor, and the accuracy of the information acquired. In order to carry out IMIR, the residual lifetime of idler rolls needs to be determined either by statistic data provided by bearing manufacturers, or by analysis result of the DS.

However, the residual lifetime of the bearing based on statistic data does not take into account the specific loading history of the bearing. In case of idler roll bearings, the load can vary significantly according to different utilized capacities. On the other hand, lifetime prediction based on the analysis of real-time monitoring data can be very complicated and time consuming.

Here we propose a SD model based LCS. A new analytical model (SD model) of idler roll load calculation has been recently developed by Liu et al [4]. With the SD model, the load on each journal bearing of idler rolls can be calculated according to different utilized capacities of the belt conveyor. Experiments show that the SD model has a good correlation with the actual load on each roll support [19].

## 5.1 MODEL

In the SD model based LCS, a number of elements are included:

- the belt conveyor
- the bulk material
- the bearings
- the maintenance trolley
- the inspection requirements
- the servicing aspects
- and the data analysis

In the proposed model, the cumulative capacity diagram (for example Fig. 6) of the conveyor provides essential information regarding the utilization of the conveyor. The cumulative capacity diagram shows the historical record of the capacity of the conveyor indicating the bulk load acting on the idlers during their lifetime. All days with the same capacity level are taken together and plotted against the corresponding number of summarized days.

In order to obtain a precision load on each idler roll bearing, the parameters of the bulk material, density and internal friction angle e.g., need to be added into the model.

## 5.2 ESTIMATION OF RESIDUAL LIFETIME

Without accurate prediction model of the load exerted on the roll bearing, the LCS developed in [3] applied deviation parameter d and safety factor f to estimate the residual lifetime of the bearings.

Now with the prediction of SD model, the load history of each roll bearing can be derived according to the cumulative capacity diagram. Based on the loading history, a physical residual lifetime prediction model of idler roll can be developed by applying bearing L10 lifetime equation. From the SD model, the total normal force $F_{NG,w}^{SD}$ and axial force $F_{NA,w}^{SD}$ on each wing roll are as follows [19]:

$$F_{NG,w}^{SD} = F_{NG,bulk,a} + F_{NG,bulk,p} \tag{1}$$

$$F_{NA,w}^{SD} = \left( F_{NA,bulk,a} + F_{NA,bulk,p} \right)/3 \tag{2}$$

Where,

$$F_{NG,bulk,a} = \frac{1}{4}\rho g l K_a \left( \cos\alpha \tan\beta + \sin\alpha \right) L_1^2 \cdot \frac{\cos^2\alpha}{\cos^2\beta}$$

(3a)

$$F_{NA,bulk,a} = \frac{1}{4}\rho g l K_a \left( \cos\alpha \tan\beta + \sin\alpha \right) \tan\varphi_w L_1^2 \cdot \frac{\cos^2\alpha}{\cos^2\beta}$$

(3b)

$$F_{NG,bulk,p} = \frac{1}{4}\rho g l K_p \left( \cos\alpha \tan\beta + \sin\alpha \right) L_1^2 \cdot \frac{\cos^2\alpha}{\cos^2\beta}$$

(3c)

$$F_{NA,bulk,p} = \frac{1}{4}\rho g l K_p \left( \cos\alpha \tan\beta + \sin\alpha \right) \tan\varphi_w L_1^2 \cdot \frac{\cos^2\alpha}{\cos^2\beta}$$

(3d)

in which $\rho$ is the density of bulk material, $l$ is the idler spacing, $K_a$ is the coefficient of active stress, $K_p$ is the coefficient of passive stress, $\alpha$ is the idler trough angle, $\beta$ is the surcharge angle, $\varphi_w$ is the wall friction between bulk material and the belt, $L_1$ is the length of bulk material on the wing belt section.

With known normal forces and axial forces on two wing rolls, the vertical force equilibrium of

one idler spacing can be built, from which the vertical (normal) force $F_{NG,c}^{SD}$ on the centre roll can be obtained:

$$F_{NG,c}^{SD} = m_{bulk}' g l - 2 \cdot F_{NG,w} \cdot \cos\alpha - 2 \cdot F_{NA,w} \cdot \sin\alpha \quad (4)$$

Fig. 6 shows the cumulative capacity diagram of a 12.5 km long belt conveyor. The design capacity of the conveyor system is 8700 t/h. It is obvious in Fig. 6

, however, the conveyor is running under the nominal capacity in most time.
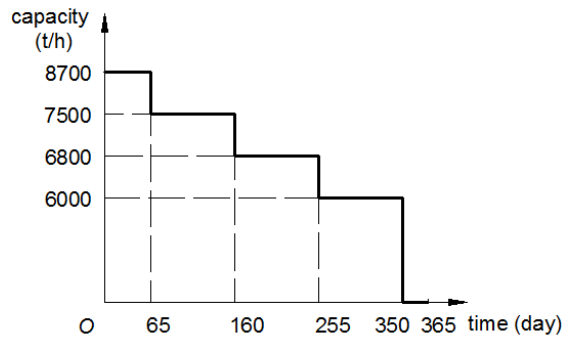


Fig. 6 Cumulative capacity diagram

Till the realization of the SD model, it was widely accepted that the loading ratio between the wing roll and the center roll is 1:4, regardless of the actual loading condition of the conveyor. Obviously it is not accurate, since it can be easily understood that higher ratio of bulk material will be loaded on the center roll if the loading capacity of the conveyor becomes lower. Table 1 and 2 show the calculation results of the load on three-roll trough idlers from SD model and traditional method.

| Capacity (t/h) | SD model | | |
|---|---|---|---|
| | $F_{NG,w}^{SD}$ (N) | $F_{NA,w}^{SD}$ (N) | $F_{NG,c}^{SD}$ (N) |
| 8700 | 1354 | 782 | 4911 |
| 7500 | 1192 | 703 | 4450 |
| 6800 | 1100 | 659 | 4172 |
| 6000 | 1003 | 611 | 3844 |
| 0 | 722 | 400 | 850 |

Table 1 Calculation of load on each roll from SD model

| Capacity (t/h) | Traditional method | | |
|---|---|---|---|
| | $F_{NG,w}^{T}$ (N) | $F_{NA,w}^{T}$ (N) | $F_{NG,c}^{T}$ (N) |
| 8700 | 1686 | 961 | 4644 |
| 7500 | 1550 | 884 | 4100 |
| 6800 | 1470 | 838 | 3782 |
| 6000 | 1380 | 787 | 3420 |
| 0 | 722 | 400 | 850 |

Table 2 Calculation of load on each roll from traditional method

From Fig. 6 and Table 1, the cumulative load factor $\bar{K}$ can be calculated as follows:

$$\bar{K} = \frac{1}{\sum (t_i \cdot K_i^3)} \quad (5)$$

where, $t_i$ is the ratio between the days of each capacity level versus the total days (365 days), $K_i$ is the ratio between the bearing load at each capacity level versus the bearing load under the design capacity. In this case, the cumulative load factor for center roll bearings can be calculated $\bar{K}_{center}^{SD} = 1.54$, $\bar{K}_{center}^{T} = 1.67$. And the cumulative load factor for the inner journal bearing of the wing roll $\bar{K}_{wing}^{SD} = 1.64$, $\bar{K}_{wing}^{T} = 1.43$.

In order to calculate the residual life, the basic L10 lifetime equation can be applied [20]:

$$L_{10} = \frac{\bar{K} \times 10^6}{60n} \left(\frac{C}{F}\right)^3 \quad (6)$$

where $C$ is the dynamic load rating from bearing manufacturers, $n$ is the rotating speed of the roll. The residual life length of the center roll and wing roll are summarized in Table 2.

| residual lifetime of center roll SD model (hour) | residual lifetime of wing roll SD model (hour) |
|---|---|
| 35617 | 122861 |
| residual lifetime of center roll traditional method (hour) | residual lifetime of wing roll traditional method (hour) |
| 48144 | 90840 |

## 5.3 MAINTENANCE STRATEGIES

Four maintenance strategies have been discussed in [3]:

Strategy 1: Inspection only forward, servicing immediately if required. Do nothing on return.

Strategy 2: Inspection and servicing both forward and backward.

Strategy 3: Inspection only forward, serving only on return.

Strategy 4: Inspection only forward, data mining at tail, servicing on return.

All the above four strategies can be suitable for both fixed maintenance time interval and flexible maintenance time interval. In [3], the fixed maintenance time interval was determined by assuming a uniform distribution of failures of random bearings. In reality, however, it may be expected that an exponential distribution of bearing failures exists.

## 6    FUTURE DEVELOPMENT

Cloud-based intelligent maintenance

Considering the large amount of idler rolls in large-scale belt conveyor, one foreseeable bottleneck in intelligent maintenance is the efficient processing and analysis of the big data collected from the data acquisition subsystem. In this sense, cloud computing can be a promising solution. Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be provisioned and released with minimal management effort or service provider interaction (NIST, 2011)

Fig. 7 shows a hypothetical architecture of cloud-based intelligent maintenance. Gates collect inspection data from each sensor, and then send the data to the condition database in cloud via the route. Data processing and intelligent decision-making algorithms are also stored in the cloud. The collected data will be quickly processed and decisions will come up whether maintenance activities are necessary. All the decisions of maintenance activities and predictive results of lifetime of idler rolls will be stored in the maintenance database in the cloud. The conveyor operators can easily get access to the maintenance database. Meanwhile, if an idler roll replacement decision is made, the decision will be automatically sent to the replacement subsystem with detailed information such as position of the failed rolls.

## 7    CONCLUSIONS AND RECOMMENDATIONS

Recent development of intelligent maintenance system for large-scale belt conveyor idler rolls has been discussed in this paper. Available techniques were presented and compared. It has been found that robotic replacement has been realized technically, more challenges lie in the reliable condition monitoring of idler roll, efficient decision-making and appropriate maintenance logic control subsystems.

Another recommendation for future research is to develop flexible maintenance strategy based
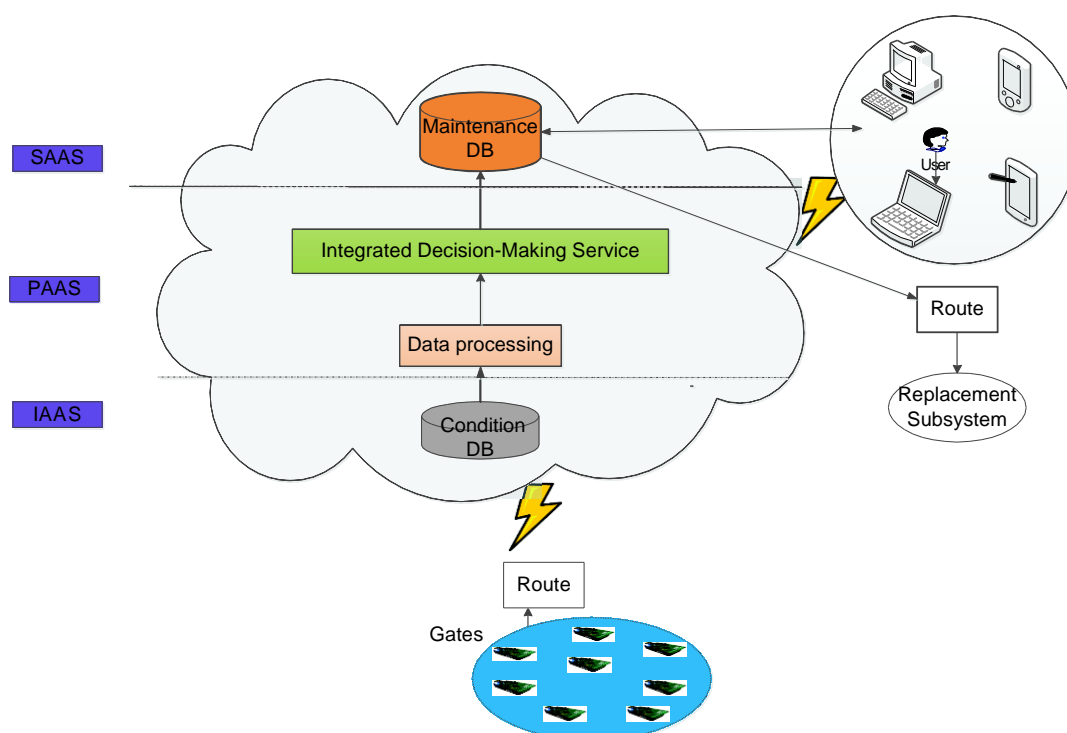


Fig. 7.  Architecture of cloud-based intelligent maintenance

on so called Physics-Data Integrated Model. The monitoring result of individual roll bearing can be integrated into the physical residual lifetime prediction model (for instance SD model) to update the current state of the physical model. In this case, the general physical model is individualized according to real-time monitoring data. The individualized physical model can be rather more reliable for the prediction of residual lifetime of individual roll compared to statistic data or only real-time data analysis. With the support of Physics-Data Integrated Model, a flexible maintenance interval can be determined, resulting in large improvement in the performance of IMIR.

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