UDC 621

INTEGRATION OF THE SYSTEM OF DIAGNOSTICS OF INDUSTRIAL EQUIPMENT AND ENTERPRISE ASSET MANAGEMENT SYSTEMS USING FIWARE FRAMEWORK[1]

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The purpose of this paper is to present integration of vibrational diagnosing system with a FIWARE framework. This integration increases scalability of the system and facilitates the further developing of the system. Designed system has been implemented and tested in real life conditions. The best economical effect can be achieved if the proposed system is used in full-automated manufacturing. Integration with subsystems of enterprise management of Industry 4.0 trend has been proposed. Operative recomputing of workflow and costs of each of alternative scenarios can maximize advantages of continuous automated monitoring of technical state of equipment. Advantages of application of the FIWARE framework for design of proposed Cyber-Physical System have been shown.

Keywords: *cyber-physical system, Industry 4.0, FIWARE, context broker, smart factory, vibrational diagnosing, system modeling, function modeling, information system, industrial control system.*

Introduction. Non-destructive diagnostics methods are rapidly developed for the last decades. Vibrational diagnosing is the one of the most effective methods of non-destructive equipment diagnosing. Vibrational signal is an immediate result of machine parts interaction between themselves and with environment [1–4]. Thus, vibrational signal contains full information about equipment state. It consists of a lot of components different nature that are informative features of equipment state. Vibrational diagnosing system extracts these features, evaluates their significance and occurrence stability. Technical state of each element of machine and its state in general are monitored.

Depending on used technical processes and equipment kind different maintenance approaches may be used:

– breakdown or run to failure maintenance. Machine is allowed to run until its failure. Its parts are repaired or replaced only after its damage. Such kind of maintenance may be acceptable if equipment shutdowns do not break workflow or idle losses are not appreciable. The approach has a few serious disadvantages. Large nomenclature of details is needed to replace details fast. Equipment is worn faster because of increasing of temperature and vibrational loads. Installation errors, that are the most frequent reason of damages [5], are not corrected;

– preventive or time-based maintenance. Maintenance activities are conducted at predetermined calendar time intervals or equipment running hours. This can prevent unexpected failure and destruction of equipment. Drawbacks of this method are numerous unneeded assembling operations, destruction and removing of good parts or missing of defective ones. Probability of mounting errors is higher;

– predictive or condition-based maintenance. Maintenance activities are conducted only when a functional failure is detected. Then significant increasing between-repair intervals (25–40%) and improvement of production efficiency (2–10%) [2], reducing need for large inventory spares and mistakes in mounting [5] are possible. But incorrect machine state assessment may increase damage. Complex diagnosing equipment and qualificated personnel are required to prevent this;

– proactive or prevention maintenance. The best result may be achieved if reasons of equipment failures are eliminated in addition to equipment state monitoring. Simple procedures are used to significantly decrease mounting mistakes and therefore equipment damages [2]. But vibration diagnosing methods can improve detection and correction of installation errors [2].

Choice of suitable approach depends on relation of diagnosing cost and losses caused by damages and idle of equipment, workflow and equipment costs. In practice, combined approach can be used [2; 6] (figure 1) Diagnosing system, considered in this paper, realizes predictive maintenance. The main advantages of this system are early defect detection, broken element and kind of defect recognition, the elements remaining useful life (RUL) estimation. Equipment idle time and its repair cost may be reduced due to better maintenance scheduling. The purpose of considered in this paper system is provide information for realization of predictive and proactive maintenance.

Vibrational diagnosing can be effective only if information about technical state of equipment is operatively applied. It is possible in full automated manufacturing. Many subsystems, such as scheduling, process control, sparces supply and maintenance, should be integrated. Next Generation Services Interface (NGSI) API

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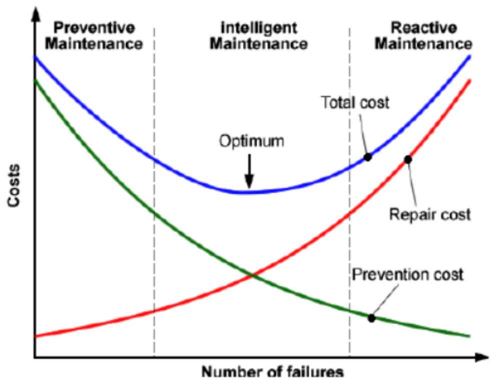
is appropriate solution: it realized system-independent approach means to advertise the existence of data with particular categories and provide it using an appropriate adaptor [7]. It can share information between various subsystems that even can be not aware about each other. This means that any of already deployed system of plant management can be extended, special adaptor is only needed. Any of third-party solution having such adaptor can easily be applied.

The paper is devoted to integration of industrial equipment vibrational diagnosing system with ecosystems based on FIWARE framework [8]. Such integration has been implemented [9]. The rest of this paper is organized as follows: maintenance approaches have been described, appropriacy of used approach have been grounded, context management conception has been discussed, the current implementation has been briefly described, integration of diagnosing system with business administration system has been proposed. Questions for the further research have been raised in the conclusions section.

Figure 1. – Costs of maintenance of different strategies [6]



Data acquisition and processing. Vibration is measured by sensors mounted near important details, for example, in bearing housings, in such way as to pass vibration freely in all frequency ranges [10–12]. This means secure direct contact, minimum of irregulations and hard material on the way of wave propagation (to avoid resonances, achieve good high-frequency response) [5] and low distance from vibration source to sensor to pass high frequencies dissipating faster. Acceleration, velocity and displacement probes can be used, but accelerometers are the most widely spread [10]. They are reliable and have wide frequency response range [5]. Velocity can be obtained by integration of acceleration, integral of velocity is displacement, and vice versa. All the signals carry the same information, but methods of diagnosing are developed for the concrete type of the signal, e.g., misalignment is diagnosed analyzing displacement (especially trajectories) [2; 10; 13], defects of rotary equipment, especially rolling bearings, are detected processing acceleration and its envelope [2; 3; 14]. Components of acceleration signal have comparable magnitudes in different frequency ranges, that makes them convenient for analysis [2]. Some standards normalized vibrational velocity [2]. Vibrational diagnosing system requires telemetry equipment to transmit observed vibration. It includes multichannel analog to digital (ADC) converter. Note, that the channels should be synchronized with high accuracy for some tasks, such as shaft orbit analysis (acquisition of vibration from installed closely sensors in perpendicular directions) and phase measurements (analysis of phases at distinct ends of shaft to discriminate types of imbalance or rotor bent [10]). Analysis of amplitude spectrum only does not require synchronization, but signals should be observed simultaneously, especially if they are non-stationary by amplitude (examples [11]) or frequency (examples [15; 16]). Telemetry block transmits recorded data through WiFi or Ethernet connection to cloud server where the main signal processing program is deployed. It's grounded by high computational cost of algorithms of extraction of informative features and lack of need in real time processing. The system is able to process third-party data and share observed vibration and its meta through NGSI adaptor, particularly, subscribing to updates of third-party observations and updating according entities.

Informative features extraction methods. The simplest diagnosing methods are based on signal statistical parameters. Signals root mean square (RMS) is used to compare signals power. Equipment state control standards (ISO 7919, ISO 15242) assign vibration RMS or peak-to-peak value permissible values for different types of equipment. Also vibration growth is limited. For early detection of defects it's appropriate to trend these parameters [2; 5]. Additional parameters are also recommended for trending. Peak factor is ratio of peak and RMS values. It's effective to detect shocks. Its trending is important because its value grows when pulses energy increases, but the further degradation leads to noise increasing and decreasing of peak factor value. Shock pulse method (SPM) is extension of peak factor mearurement. The core of the method is measurement of amplitude of spikes at resonant frequency of sensor or elements. Shocks in defective bearings excite pusles at resonant frequencies of elements and sensor. Then shocks amplitude is related to noise level. Further modification of SPM leads to frequency domain methods (analysis of pulses envelope spectrum) and time domain methods (demodulation and estimation of pulse repetition rate) [17].

Analysis of statistics and power of vibration can indicate technical state of group of elements under sensor in general, cannot indicate a certain faulty element and its defect [18]. Information about technical state of each element is required to reduce maintenance costs as well as disassembling and installation operations leading to errors and thus failures. Vibrational signal consists of various components of different origin related with periodical impact of unbalanced masses, kinematic forces and shocks [1–4; 10]. These components should be selected and discriminated. Mainly frequency domain analysis of vibration and its envelope [1–4; 10; 14; 19] is used to detect a certain defect of a concrete element, especially incipient defects, time-frequency methods are applied for preprocessing of the signal [11; 20] as well as for informative features selection [21; 22]. Then, remain resource of each element can be estimated and thus maintenance can be planned more rationally [5; 23].

To estimate the current state of equipment relying on various features, trending and comparison of parameters of signal with their previous values [5; 11], thresholding of parameters using maximum likelihood rule [24; 25], Big Data analysis [23]. The system evaluates the current technical state of equipment and its units as well as its remaining useful life (RUL) that is approximate time of degradation of the machine to its damage or dangerous faults. RUL estimation is based on trending of informative features [25] or random process analysis (Markov-based models, Wiener or Gaussian processes) [23]. RUL is based on estimations of the current technical state, cannot be evaluated exactly and unreliable if defect evolves abruptly, then both of the current state and RUL are used for decision making, especially rational scheduling [23]. Considered in this paper diagnosing system can estimate the current state as well as RUL, recommendations on maintenance, such as align shafts or replace bearing are provided.

Unexpected failures. Maintenance and implementation of recommendations can also prevent developing of new defects. Poor alignment of machines is the main reason of their malfunction [10]. Accurate alignment is reported to enhance average life time of bearings and couplings by 3…8 times, reduce maintenance costs by 5…7%, increase interrepair interval by 10…12%, reduce unexpected halt of equipment, caused by misalignment, by 2 times [2]. Basic reasons of failure of rolling bearing are reported [2]: 40% – lubrication defects, 30% – wrong assembling and mounting, 20% – other reasons related with wrong exploitation, such as overloads, strong vibration, etc., 10% – normal wear. Vibration of bearings is excited by their normal work as well as defects of bearing or related elements such as shaft, that increases vibration load [2]. Diagnosing system can detect incipient defects as well as errors of installation, and user can prevent faster degradation of equipment. Maintenance and elimination of named reasons of failures can offer significant economical advantage if all actions are conducted timely and do not interfere with production plans. Satisfy contradictory conditions is task of scheduling system. High priority, unexpected repair works can be reduced [26]. It should consider probabilistic nature of failures.

Malfunction of equipment units is a random event by its physical nature due to variability of parameters of details and operating conditions. Thus, it may be described by failure probability density function (PDF), hazard rate and reliability function [27; 28]. Failure PDF of rolling bearings is reported to be like one depicted at figure 2, *a*. It can be approximated as $f(t) = \lambda e^{-\lambda t}$. This PDF describes electric motor to failure if λ is motor failure rate [28]. Failure (hazard) rate is approximated by bathtub function (figure 2, *b*) [27; 28] in various fields of technique: the first period is early failure, burn-in period; useful life period and wearout period. Probability of breakdown of is higher at burn-in period due to errors of manufacturing and poor quality control [27; 28]. Additionally, errors of mounting discussed above can increase failure rate [28]. During useful life, failures are caused by a lot of random factors, failure rate is stable [27; 28]. In wear-out period, aging factors are the reason for breakdown: fatigue, cracks, friction and corrosion, etc. Ageing of the components is accelerated by defects, such as imbalance or misalignment [28]. Constant failure rate can be described by exponential PDF of failure, rate of mechanical systems can be described by normal PDF, wear-out period can be described by Weibull distribution [27]. Bathtub curve can be approximated by sum of three Weibull functions with different parameters [29]. Hazard function is also reported to have different shape near zero and do not decrease [29].

Maintenance costs (MC) can be estimated using the methodology [30]. MC of preventive approach can be evaluated according to the expression:

$$MC = C_w + C_{pr} = (C_w^u + C_w^p) + (C_{pr}^u + C_{pr}^p), \quad (1)$$

where C_w^u is unexpected failure work (labor + sparces);

C_w^p is planned maintenance work;

C_{pr}^u is production costs during unexpected idle;

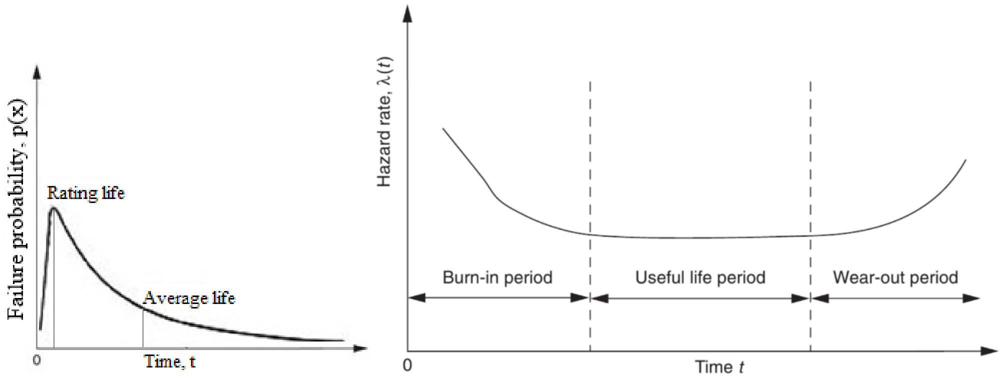
C_{pr}^p production costs during planned maintenance idle.

Unexpected expenses are accounted for probability of failure before assigned time of maintenance. Predictive maintenance, together with proper scheduling, can reduce unexpected costs as well as planned, e.g., interrepair period can be 15–30% shorter due to unreasonable scheduled works [30].

Conclusions of the section:

– preventing of all failures by periodical maintenance is impossible, unexpected failures can interrupt workflow and delay of production;

– periodical maintenance leads to additional expenditures;
– mounting errors increase failure rate. They can be eliminated by diagnosing and operative maintenance;
– interrepair period is decreased in case of constant period maintenance, that can lead to additional mounting errors.



a *b*

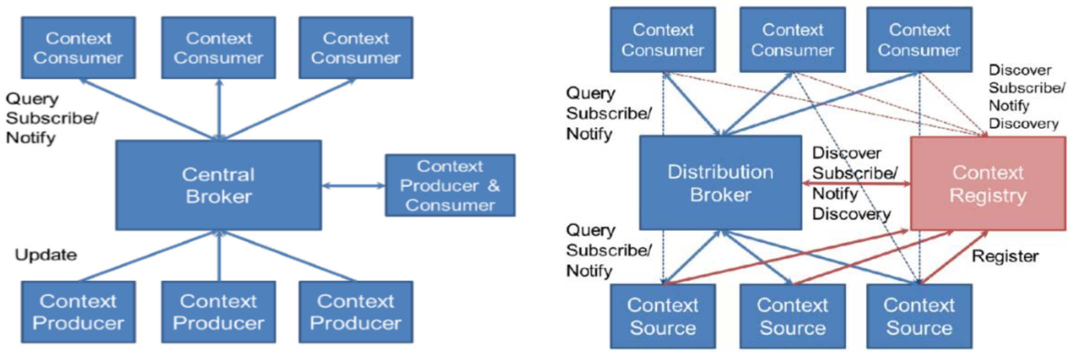
a **– failure PDF [31];** ***b*** **– hazard rate [28]**

Figure 2. – Functions describing probabilistic nature of failure

Integration of diagnosing system with FIWARE framework

Context broker. Interest to development of Cyber-Physical Systems (CPS) growing fast during a few last years. CPS is kind of ICT systems (sensing, actuating, computing, communication, etc.) embedded or software integrated in physical objects, interconnected including through the Internet, and providing citizens and businesses with a wide range of innovative applications and services [32]. Its advantages are increasing of flexibility and higher integration of production system [33]. Application of CPS in industry improves continuous monitoring and remote control of workflow and technical state of equipment [34]. Open design and standardized platform is demanded [32]. FIWARE framework can be convenient solution.

In FIWARE, various producers and consumers of data are interrelated through Context Broker (CB). Context is any actual information about entities: their properties and interrelations with other entities [7]. Each source is registered as entity in the common data base. Virtual entity is updated by actual metadata containing any information about real object: its coordinates, sensor readings, timestamps, etc. Consumer of data should discover existing producers of information. It sends request to CB and receive which sources match conditions of request. In next time consumer can request data or subscribe on updates of any selected producer. Possible schemes of data communication are presented at figure 3.



a *б*

a **– centralized broker;** ***b*** **– distributed broker**

Figure 3. – Context Broker based architectures of integration [7]

Configuration depicted at figure 3, *a* is more proper for small systems. The only central broker is used for information interchange. Geographically distributed systems can be realized as it showed at figure 3, *b*. Central database is used for metadata exchange only, large amounts of data can be sent directly from producer to consumer. Advantages of CB application are: flexible system of requests, independence of integrated systems and potentially limitless of their amount, easy scaling and, unlike data lakes, it does not requires regular cleaning up [7].

The current implementation. Scheme of realized integration of diagnosing system [9] has been shown at figure 4. Telemetry blocks (Vbox device) receive signals of accelerometers, translate them to *.wav files and upload to Vibrobox Cloud service for the further processing, informative features selection and diagnosing. Metadata, such as uploading link, calculated at Vbox device statistics of vibration signal (RMS, peak factor, recording date, etc.), is updated in CB. Broker is deployed in Docker container at cloud service. Microservice Draco is used for storing history of updates in Mongo Database. The service is subscribed on updates of the sensor entity. The system have been deployed and tested under Linux Ubuntu and Windows 10 systems [9]. The following KPIs were performed [9]:

1) metadata of signals were successfully transmitted from Vbox telemetry units through FIWARE components to cloud processing platform;
2) time of deploying of diagnosing system for new type of equipment is less than 14 days from sensors installation till full readiness system for usage, including self-adaptation and adjustment;
3) the system can be scaled in 5 days or faster for the similar type of equipment if its kinematic scheme is known;
4) idle time of equipment has been reduced by 10% during testing on enterprise.

Integration with smart scheduling systems. Smart scheduling can decrease idle time as well as delay of production manufacturing. Shop-floor scheduling algorithms can be used (artificial intelligence [35], genetic algorithms or fuzzy logic [36], agent modelling [37; 38], risk minimization or gain maximization [39], usage of constraints on temporal variables [40]). Note, that these algorithms can dynamically update schedule, unlike proposed system that minimizes losses by optimizing time to maintenance [41]. Utility maximization approach is selection of several alternatives. Each of them is according to utility or risk, that is calculated as weighted sum of a few parameters. It can consider many factors, specificity of workflow and enterprise, time of delivery of production, etc. For example, delay of production or leads to increasing of risk or decreasing of utility. Decreasing of idle time leads to increasing of utility. The simplified scheme of integration of such scheduling framework with monitoring system, relying on [39], is presented at figure 5. Input of decision making block is variables under weighting. Output of monitoring system is also taken into account. For example, delay of maintenance can increase risk if equipment state degrading fast. System decides what of alternative scenarios have less risk: losses if production delayed or losses on equipment failure. Maintenance costs (1) are also can be taken into account.

Diagnosing system can estimate technical state and RUL that can be used for decision making by humans. Considered diagnosing system can give recommendations based on actual state and RUL, for example, replace the bearing during the month. In case of full-automated manufacturing with smart decision making, recommendations can be used for composing of alternative scenarios further selecting as described above, e.g., stop machine now and conduct alignment, replace bearing, etc., or finish the current production task and conduct maintenance after. If maintenance operation is considered as one more operation at the same machine, approach of usage of constraints on time variables can be used to compose scenarios for their further selection. Starting time of each operation is limited by set of constraints [40]. Let O_i be the *i*-th operation, s_i be its starting time, p_i be processing duration, c_{max} be total operation duration. The condition (2) sets end time and duration of each operation. Rules (3), (4) assign right order of operations [40]:

$$s_i + p_i - c_{max} \le 0, \forall i \in O, \tag{2}$$

$$2x_{i,j,m} + 2x_{j,i,m} - v_{i,m} - v_{j,m} \le 0, \forall i, j \in O, J_i \ne J_j, \forall m \in M_i \cap M_j, \tag{3}$$

$$x_{i,j,m} + x_{j,i,m} - v_{i,m} - v_{j,m} \ge -1, \forall i, j \in O, J_i \ne J_j, \forall m \in M_i \cap M_j, \tag{4}$$

where i, j are operation iterators;
m is number of machine tool;
$x_{i,j,m}$ is equal to 1 if operation O_i is processed before operation O_j on the tool m and is equal 0 otherwise;
$v_{i,m}$ is equal to 1 if operation O_i is assigned to the tool m and is equal to 0 otherwise;
M_i is set of machine tools available for operation O_i;
J_g is the g-th job.

Other conditions, such as energy consuming, can be taken into account [40]. Using the same methodology, rule that define order of operations of maintenance and production (5) is proposed. It means that maintenance operation can be assigned only if maintenance of according machine tool is prescripted, and production operation cannot be assigned in another case.

$$v_{i,m} \cdot R_i - S_m = 0, \tag{5}$$

where R_i is equal 1 if O_i is maintenance, repair operation, 0 otherwise;
S_m is equal 1 if maintenance of the m-th tool is prescripted, 0 otherwise.

New operations excepting maintenance are not appointed if the current state degraded to damage level. Workflow is also interrupted after RUL has expired. Constraint (6) allows exploitation of equipment if its state is appropriate and factors (such as RMS of vibration or level of some harmonics) are not exceed prescribed by standards [2; 5; 10] level. The condition can be used for planning operations of the machine whose the current state is satisfactorily but its soon degradation is expected:

$$v_{i,m} \cdot CS_m \cdot RUL_m \cdot L_m = 1, R_i = 0\,, \tag{6}$$

where CS_m is equal to 1 if the current state of the m-th tool is good, 0 otherwise;

RUL_m is equal to 1 if remaining useful life has expired, 0 otherwise;

L_m is equal to 1 if vibration level is lower assigned threshold and is 0 otherwise.

System of equations can be more complex since halt of the m-th machine leads to interruption of the whole chain of production.

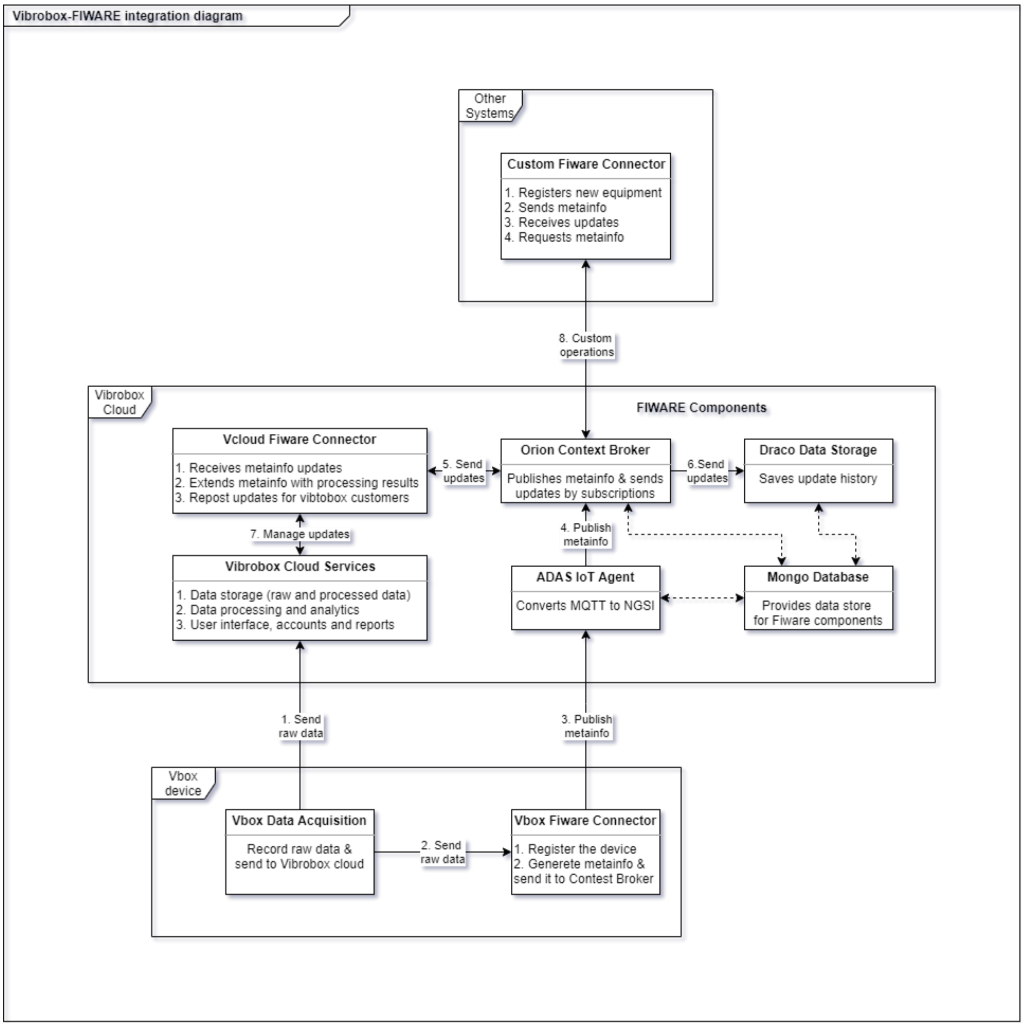


Figure 4. – Scheme of realized integration of diagnosing system with FIWARE components

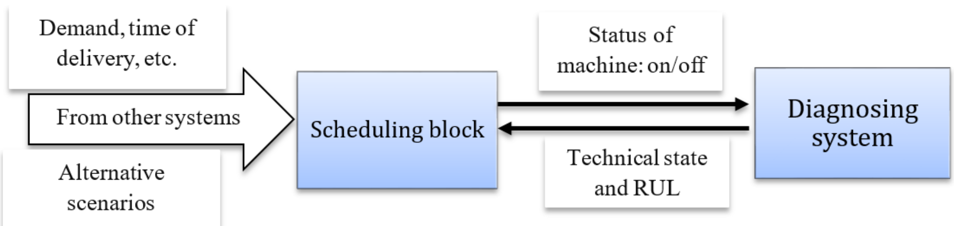


Figure 5. – Simplified scheme of interrelations between scheduling and monitoring subsystems

Scheme of proposed system is presented at figure 6. Alternatives construction block prepares a few of possible scenarios of production and maintenance according to (2)–(6). Maintenance is not included in schedule if equipment state is good. Scheduling block selects one consequence of operations which have maximum gain. Both of these blocks are interrelated with each other, maintenance system and additional subsystems (such as materials supply) through CB. Interaction between systems is unified, one shouldn't change anything in one system if another is modified or added. Each of them obtains actual required information.

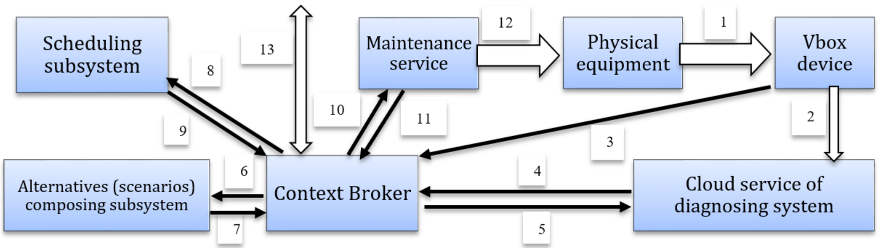


Figure 6. – Scheme of integration of vibration diagnosing system and business management system

Vbox device observes vibration produced by physical equipment, link 1, converts it to convenient for processing form and sends it to cloud service, link 2, updates the sensors entities, link 3. Cloud service can update entities of machine and its units under diagnosing by their actual estimations of technical state, RUL and recommendations, link 4. Such recommendations as "conduct maintenance of the *m*-th machine in *x* days" or prescriptions to halt machine immediately (if it goes to breakdown) can be used for automatic scenarios composing, detailed recommendations, such as "replace the *n*-th bearing of the *m*-th machine in *x* days", are useful for personnel of maintenance service. Cloud service can receive updated of the third-party observations, link 5, and update in the similar way according equipment entities. Integration of data acquisition subsystems (Vbox device) and cloud service with CB (links 1–5) is currently implemented (see figure 4). Scenarios composing subsystem receives notifications and updates of equipment entities as well as other controlled parameters (production demand, etc.), link 6, updates entity of production scenarios of the current factory, link 7. It can be implemented according to (2)–(6) and should take into account workflow of the concrete enterprise and selected maintenance strategy – see figure 1. Scheduling subsystem receives notifications and updates of scenarios and variables that influence on cost of each of alternatives, link 8, and updates schedule, workorders and maintenance prescription entities and equipment status (on/off), link 9. Maintenance service receives prescriptions and recommendations, link 10, it can request sparces and update required time of maintenance, link 11. The 12-th link designates repair works conducted by maintenance service and changing equipment state. The 13-th link signifies interrelations with other enterprise administration systems (demand, supply, etc.) and third-party services.

Each of sensors, machine units and the whole machines are distinct entities. Sensors entities hold information about recent observation and the most necessary characteristics of vibration (RMS, peak) required according to standards. Machine units, as well as the whole machine, are characterized by their technical state and RUL. State of machine is estimated by the simplest integral methods and they are needed to capture breakdown if more accurate methods cannot do it. More accurate methods indicate faulty unit or even its concrete defect, evaluate its technical state. This is needed to prescript maintenance of a certain unit, decrease number of operations and probability of mounting errors. A few sensors are needed to evaluate technical state of unit or machine. Observed vibration of one or a few sensors is processed in cloud service, then it updates state and RUL of unit and the whole machine. Addition of equipment unit requires just registration of new entities (machine, its units under observation and sensors) in CB. All the rest blocks will obtain information that match their requirements automatically.

Subsystems of smart enterprise control can be integrated with FIWARE components. A lot of solutions have been already integrated [8], custom adaptor should be implemented otherwise. Once implemented, it can be deployed at any other system and scaled fast, as it has been demonstrated. The only condition is the common context definitions, such as machine, unit of machine, sensor. The system should be aware how they are related, e.g., failure of the unit or excitation of vibration at the only sensor leads to halt and assigning of maintenance of the whole machine, stop of machine leads to delay of operations of the whole production chain. Localization of the defect is needed to repair service to reduce expenditures and risk of errors.

If probability densities of units failure are estimated and production plans are known, probabilities of all possible scenarios can be evaluated. For example, for the sake of simplicity we can assume that maintenance operations are assigned in scenarios with the same probability as element failure. But selection of a certain alternative depends on many variables describing workflow, costs of production delay and potential losses of maintenance delay. Probability of breakdown of equipment in each moment leads to risk of losses due to failure of fulfillment of production plans. On the other hand, timely elimination errors of installation and other defects will reduce failure rate. It should be considered when production is planned.

Conclusions. Appropriacy of using of FIWARE framework has been shown. The framework can help to improve scalability of the system. Developing of the system of monitoring of technical state of equipment together with adaptive shop-floor scheduling leads to full-automated manufacturing. Described system can be realized at the levels of subdivisions (department, shop-floor), the whole enterprise or a few factories (hyperconnected factories [42]), it should consider modern standards and frameworks for enterprise integration and modelling, see ISO 19439. The FIWARE framework can unify interconnection between maintenance and production frameworks. The questions were raised for the following research:

– How to consider probabilities of breakdown of each element during planning of production to reduce risk of production delay?

– How to optimize scenarios construction to consider different probabilities of failure of each element during its life time?

– How to calculate costs of each of scenario considering technical state, RUL of elements and recommendations of diagnosing system depending on workflow and loading of equipment?

– How to integrate the system at different levels, e.g., to connect maintenance, scheduling, etc. systems at each subdivision independently and connect them at higher level or build the whole factory/group scheduling, maintenance, etc. systems?

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ИНТЕГРАЦИЯ СИСТЕМЫ ДИАГНОСТИКИ ПРОМЫШЛЕННОГО ОБОРУДОВАНИЯ И СИСТЕМ УПРАВЛЕНИЯ ПРЕДПРИЯТИЕМ ПРИ ПОМОЩИ ФРЕЙМВОРКА FIWARE

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Цель настоящей работы – описать интеграцию системы вибрационной диагностики с фреймворком FIWARE. Данная интеграция повышает масштабируемость системы и способствует ее дальнейшему развитию. Разработанная система реализована и опробована в реальных условиях. Наилучший экономический эффект от внедрения данной системы может быть получен в случае, когда она применяется в полностью автоматизированном производстве. Предложен вариант интеграции с подсистемами управления предприятием тренда Индустрии 4.0. Оперативный перерасчет техпроцесса и стоимости каждого из альтернативных сценариев потенциально максимизирует преимущества непрерывного автоматизированного мониторинга технического состояния оборудования. Показаны преимущества применения фреймворка FIWARE для разработки предложенной киберфизической системы.

Ключевые слова: *киберфизическая система, Индустрия 4.0, FIWARE, брокер контекста, умная фабрика, вибрационная диагностика, системное моделирование, функциональное моделирование, информационная система, автоматизированная система управления.*