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Department of Instrumentation and Control Engineering

Systém vzdáleného monitorování spotřeby energií v průmyslové výrobě

Remote monitoring system of energy consumption in industrial production

Master Thesis

2020

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Study program: N2301 Mechanical Engineering
Field of study: 2301T034 Instrumentation and Control Engineering
Supervisor: Ing. Cyril Oswald, Ph.D.

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Studijní program: **Strojní inženýrství**

Studijní obor: **Přístrojová a řídicí technika**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Systém vzdáleného monitorování spotřeby energií v průmyslové výrobě

Název diplomové práce anglicky:

Remote monitoring system of energy consumption in industrial production

Pokyny pro vypracování:

Navrhněte a realizujte systém vzdáleného monitorování spotřeby energií v průmyslové výrobě, který bude schopen vzdáleně shromažďovat, vizualizovat a analyzovat data ze senzorů spotřeby energií.
- proveďte rešerši současných systémů monitorování energií
- proveďte rešerši v průmyslu využívaných senzorů spotřeby energií a komunikace s nimi
- navrhněte a realizujte systém vzdáleného monitorování spotřeby energií

Seznam doporučené literatury:

[1] KARA S., Bogdanski G., Li W. (2011) Electricity Metering and Monitoring in Manufacturing Systems. In: Hesselbach J., Herrmann C. (eds) Glocalized Solutions for Sustainability in Manufacturing. Springer, Berlin, Heidelberg
[2] NOVÁK, Martin. Technická měření. v Praze: České vysoké učení technické, 2018. ISBN 978-80-01-06388-0.
[3] HAASZ, Vladimír, Jan HOLUB, Michal JANOŠEK, Petr KAŠPAR a Vojtěch PETRUCHA. Elektrická měření: přístroje a metody. 3. přepracované vydání. Praha: Česká technika - nakladatelství ČVUT, 2018. ISBN 978-80-01-06412-2.

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Datum zadání diplomové práce: **30.04.2020** Termín odevzdání diplomové práce: **27.08.2020**

Platnost zadání diplomové práce: ____________

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

30. 4 2020
Datum převzetí zadání

Podpis studenta

DECLARATION

I hereby declare that I completed this thesis independently with help of my supervisor. I used only resources and literature listed in the table of bibliography.

In Prague ....

Bc. David Polák

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I would like to thank my thesis supervisor Ing. Cyril Oswald, Ph.D. for consultations and his valuable insights. I am very thankful for the opportunity of working in P&G, which gave me support in writing the thesis and provided me all the energy meters and other necessary tools. I would like to express my gratitude especially towards my father Ivo, my mother Jana and my sister Agáta for lifelong support.

ANNOTATION LIST

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Keywords: Visualization, Fourth Industrial Revolution, PLC, Energy, Energy monitoring system, Schneider Electric, Power BI, SQL database

Anotace: Tato diplomová práce se zabývá postupem návrhu systému monitorování energií a jeho následným vytvořením. Práce začíná rešerší systémů monitorování energíí, dostupných elektroměrů, komunikačními standardy, systémy ukládání dat a vizualizačními platformami. S nabytými znalosti byl monitorovací systém navrhnut s ohledem na již existující řešení a vytvořen.

Abstract: This diploma thesis is about the design process of energy monitoring system and its development. The thesis begins with recherche of energy monitoring systems, available electricity meters, communication standards, data storage systems and visualization platforms. With acquired knowledge the monitoring system was designed with respect to already existing solution and developed.

Table of Contents

1. Introduction

In 2015 the phrase The Fourth Industrial Revolution was introduced by Klaus Schwab. Since then I thrived to understand its true meaning and wanted to contribute in implementation of the latest technologies. There are many components of The Fourth Industrial Revolution e.g. Smarts sensors, Predictive maintenance or Data visualization. [1]

I took an advantage of working in a factory, which was chosen by World Economic Forum as “Manufacturing lighthouse” for a successful track record of implementing technologies of the Fourth Industrial Revolution, and developed a monitoring system for energies with respect to production. The system was meant to be easily replicable across departments within the site and within other sites as well. It will become a corporate standard.

Energy consumption can be considered variable cost, which can be cut to minimum. Factories can optimize their processes, batch sizes and other factors to optimize their energy costs. One can say that by utilizing, metering and monitoring digitalization can help factories to become environment friendlier. By seeing an increase in energy consumption one can investigate what has changed in the production system. It is probably the earliest indication of any failure in the system. Thus, energy consumption monitoring is one of the powerful tools of Predictive maintenance. Even though this thesis is focusing mainly on electricity, the same principal can be used with metering of gas, water, compressed air or other measurable utilities.

While the first chapter is theoretical literature search regarding existing energy monitoring systems, electrometers and communication standards, the second is describing the process of designing the system, its development, data acquisition and shows the resulting reporting system using Microsoft Power BI.

CHAPTER 1

2. Energy monitoring systems

Energy bills are increasing due to rising energy costs and growing businesses. This impacts the results of a company and has negative effect on environment. Therefore, factories are trying to bring more clarity and transparency into their electricity billing, electricity distribution and energy controlling. From an electricity consumer perspective, a factory can be divided into three levels. Each level has different potential benefits and required degree of transparency from the application of energy monitoring systems.

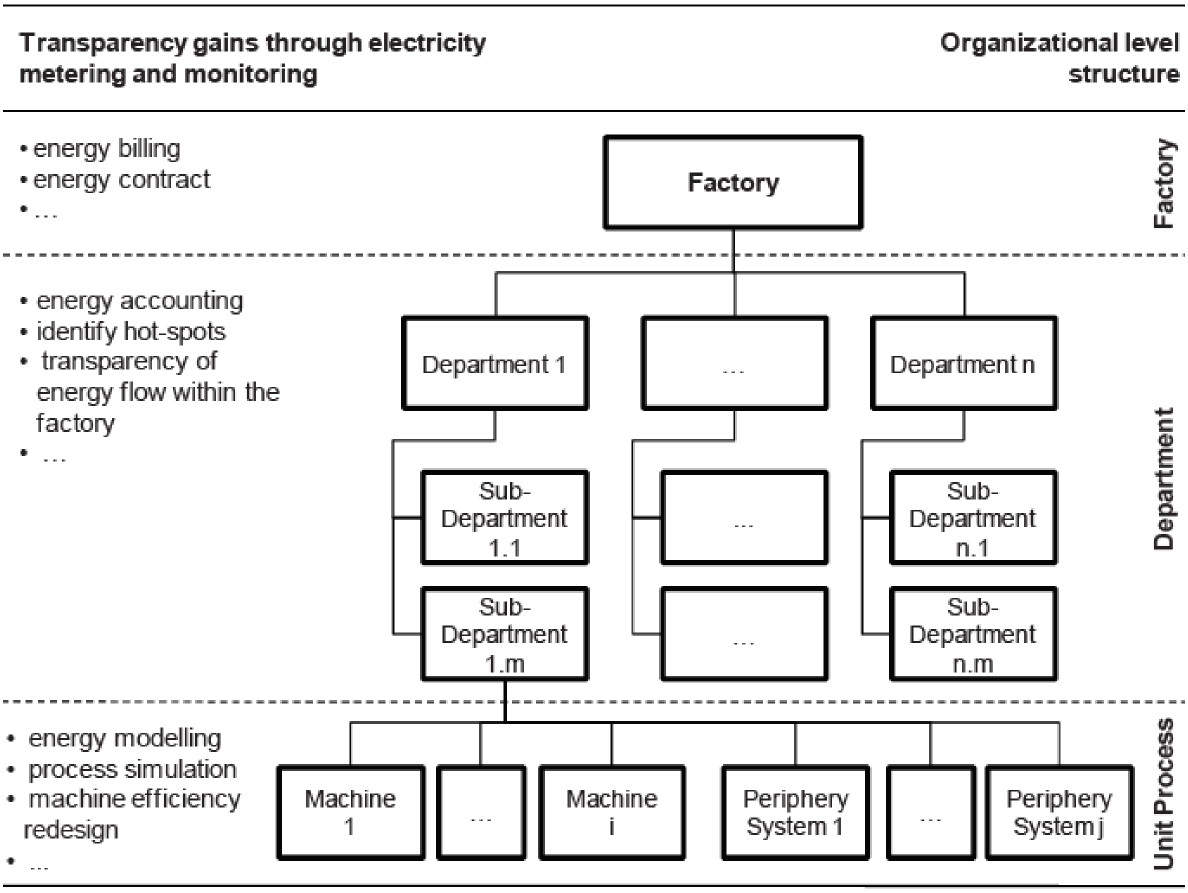

Figure 1: Three levels of a factory as a consumer of electricity [2]

"Recent publications show, that the industrialized countries are facing a multidimensional pressure from the economical, ecological as well as legislative side to shift their field of actions more towards energy and resource efficient processes and structures within their company, their products and their services to stay competitive in the global market environment." [2]

2.1. Factory level

Using the simplest initial monitoring and controlling of energy consumption factories can benefit by identifying the causes of energy demand peaks, which are being charged extra on top of normal energy consumption. Once the problem is identified, production shifts and amounts of product can be planned around it resulting in minimal impact. Energy monitoring on factory level should give the amount of clarity for time dependent controlling of energy consumption. [2]

Factory level:	
Cost factors	Total energy consumed, peak power demand, power factor limitation, THD feedback
Potential benefits enabled through electricity metering	Adaption of the electricity supply contract; preventing of peak charges through rescheduling of processes or events

Figure 2: Cost factors and potential benefits through electricity metering and monitoring on factory level [2]

2.2. Department level

Traditionally a factory consists of functional units, which we call departments. An example can be simple manufacturing factory, which is split into warehouse, making department, packing department, administration, engineering and other departments. The goal is to manage energy consumption within one department, so that the consumption curve is as flat as possible without any noticeable peaks. Energy monitoring and controlling goals of department level are noticeably in line with goals of energy manipulation of smart houses.

Department level:	
Cost factors	Specific energy consumed, peak power demand, power factor limitation
Potential benefits enabled through electricity metering	Energy intensive process scheduling; ability to deploy and track continuous improvement measures; department based energy saving targeting and benchmarking; simulative improvement of energy costing; effective utilization of secondary energy carriers produced by electricity; quantify energy savings

Figure 3: Cost factors and potential benefits through electricity metering and monitoring on department level [2]

It is proven that by introducing energy monitoring within each department, each individual feels more motivated to minimize the unnecessary energy consumption and its costs. Employees are usually responsible for areas of equipment, which leads into putting effort into reducing energy consumption and fine tuning the whole production without just shifting the consumption from one piece of equipment or area to the other. By close observation some unobvious links between energy consumption can be found and fine-tuned. Some factories went as far as planning and controlling of production with special awareness to energy consumption, which can be defined as intersection across all three level of a factory. Other factories are trying to put energy monitoring in perspective with their products and observe how much each product takes to make and try to learn how to optimize the production based on those learnings. [2]

2.3. Unit process level

On the lowest level of energy metering and monitoring, meters are attached to single machines or their components. For highly energy intensive processes, it is required to monitor each machine in order to plan production in truly optimized way. It helps to understand energetic connections between each machine and their components.

Unit process level:	
Cost factors	Specific Energy Consumption (SEC), peak power demand, power factor limitation, THD feedback
Potential benefits enabled through electricity metering	Supplementing unit process values to machine LCI databases; energy forecasting in production design, process planning and control; energy labelling of machine tools and products; specific quantification of single efficiency measures; evaluation of technical improvements; condition monitoring as a prophylactic measure in energy and resource sufficiency

Figure 4: Cost factors and potential benefits through electricity metering and monitoring on unit process level [2]

Unit process level does not only serve as a planning tool, but it can also help with condition-based maintenance and diagnostics of machines and processes. Increased energy consumption can point out the need of lubrication or it can work as early detection of tool wear. Combining energy metering and monitoring with machine control data and state can bring additional benefits. [2]

3. Electricity Metering

3.1. Physical Quantities of AC Power

In a circuit of alternating current, the instantaneous power is defined as:

$$p(t) = v(t) \cdot i(t)$$

Where *p* stands for power, *v* stands for voltage and *i* stands for electric current.

Active power in AC circuits is defined as a mean value of power (assuming harmonic content of the waveform).

$$P = \frac{1}{T}\int_0^T p(t) \cdot dt = \frac{1}{T}\int_0^T v(t) \cdot i(t) \cdot dt$$

Where *P* [W] stands for active power and *T* stands for a period of time.

In case of harmonic waveform of voltage and current:

$$P = \frac{1}{T}\int_0^T v(t) \cdot i(t) \cdot dt = V \cdot I \cdot \cos(\varphi)$$

Where *V* is root mean square value of voltage, *I* is mean square value of current and $\boldsymbol{\varphi}$ is a phase of voltage relative to current.

In case of harmonic sinusoidal waveforms mean square values are defined as:

$$I = \frac{I_{Peak}}{\sqrt{2}}$$

$$V = \frac{V_{Peak}}{\sqrt{2}}$$

Reactive power *Q* [var] is defined as:

$$Q = V \cdot I \cdot \sin(\varphi)$$

Apparent power *S* [VA] is defined as:

$$S = V \cdot I = \sqrt{P^2 + Q^2 + D^2}$$

Where *D* is distortion power produced by the harmonic components of *u(t)* and *i(t)* of a different order. [3]

3.2. Electrical Energy Consumption Measuring

Electrical energy consumption is defined as electrical work *W* [Wh] performed by electrical current between time *t1* and *t2*.

$$\Delta W = \int_{t1}^{t2} p(t) \cdot dt = \int_{t1}^{t2} v(t) \cdot i(t) \cdot dt = \int_{t1}^{t2} P(t) \cdot dt$$

Industrial consumers have been using static (electronic) watt-hour meters for several years to measure electrical energy consumption. Static watt-hour meters are more reliable then induction watt-hour meters, which have been used mainly in households, due to their safety and possibility to measure the power of strongly non-sinusoidal waveforms.

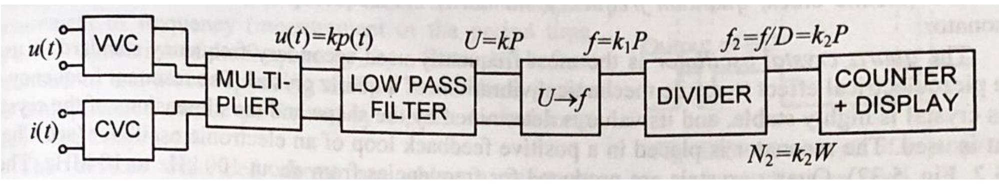

Figure 5: The principle of static (electronic) watt-hour meter using an analog multiplier [3]

In the picture VVC stands for voltage-to-voltage converter and CVC stands for current-to-voltage converter. The output voltage of an analog multiplier is converted into frequency in the U → f converter. The number of impulses at the output of U → f converter implies energy consumed *ΔW* and their frequency stands for active power. The number of impulses is usually quite high (tens of kHz), therefore there is a need for a divider between U → f converter and counter.

Digital watt-hour meters can often measure not only active power, but also reactive power, apparent power and the root mean square values of voltage and current. Thus, they can determine also reactive energy consumption ΔW_Q by integrating reactive power. [3] [4]

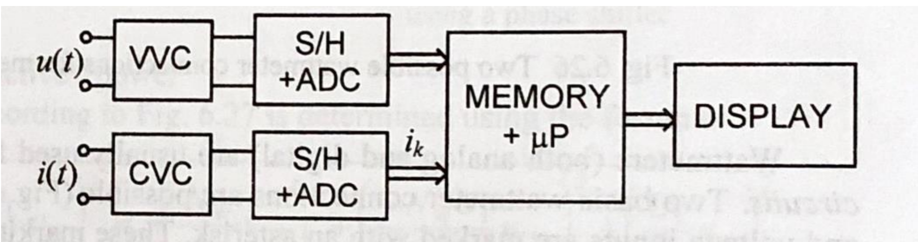

Figure 6: The principle of the electronic wattmeter using sampling method based on digital signal processing [3]

3.3. Electrometers used in Factory

With implementing a new system into production, it is always crucial to choose proper tools and devices, because each digitization project can be successful only if it has good quality data to visualize. There are multiple questions, that need to be answered before investing and installing new metering devices. The device needs to be able to measure the desired measurands, its output resolution has to be low enough (some faster processes might require resolution even lower than 1 second) and communication interface of the device has to be accessible from PLCs or gateways (these can convert communication interfaces if needed). Sometimes even the brand might come into consideration, because some companies might have better deals and it is better to have all the devices standardized. The following figure represents a selection of mostly used measuring series/types and their specifications.

Measurement instrument: Brand, series/type	Installation	Measurands*	Output resolution*	Communication interface*
IME, NEMO 96	Fixed type	V, A, W, VA, PF, THD	60 s	RS485, Impulse
Siemens, SIMEAS	Fixed type	V, A, W, VAR, VA, PF, THD	< 1s	Profibus, RS485
Schneider, Electrics, PM	Fixed type	V, A, W, VA, PF, THD	60 s	RS485, Impulse
Simpson, GIMA1000	Fixed type	V, A, W, VAR, VA, PF	1 s	RS485, Impulse
Yokogawa,	Fixed type	V, A, W, VAR, VA, PF	<1 s	Ethernet, RS485, Pulse
AccuEnergy, Acuvim	Fixed type	V, A, W, VAR, VA, PF, THD	<1 s	Ethernet, Profibus, RS485, Impulse
Janitza Electronics, UMG 604	Fixed type	V, A, W, VAR, VA, PF, THD	<1 s	Ethernet, Profibus, Impulse
Chauvin Arnoux, C.A.8335	Mobile type	V, A, W, VAR, VA, PF, THD	1 s	USB
Fluke, 434	Mobile type	V, A, W, VAR, VA, PF, THD	0.5 s	USB
Voltech, PM3000	Mobile type	V, A, W, VAR, VA, PF, THD	<10 ms	RS232, IEEE488
Load Controls, PPC	Mobile type	W	15 ms	Analogue 0-10 volts or 4-20 milliampere
National Instruments, cDAQ*	Mobile type	V, A	<1 s	USB

*the listed features are retrieved from the datasheets of the devices and are due to change in future instrument revisions

Figure 7: Selection of often found electricity meters from different vendors with important properties [2]

Choosing a device with high output resolution might result in non-precise unnecessarily expensive solution, because metering devices with output resolution higher than one second can exceed price tag of 5 000 EUR. Not only the device but also data storage requirements grow exponentially and result in additional non-negligible cost. Communication interface plays an important role as well. For slower processes, meters with RS485 are usually the right option, but if nearly real-time metering is needed, meters with Ethernet or Profibus communication interface should be the better option. Introducing a new communication interface and standard is very costly. Hence, it is very wise to spend enough time exploring all available options and choosing the one, that satisfies all requirements. [2]

3.3.1. PowerMeter PM800

PM800 series power meters are fixed type devices, which measure all three phases and neutral phase at one time. They can be used for both low and high voltage measurements. By default, they are equipped with RS-485 Modbus communication port, but they can be upgraded with Ethernet Modbus TCP/IP. Other features are digital inputs, digital outputs, alarming and THD (Total Harmonic Distortion) metering, which is very important to monitor and control. It can measure both active power and electrical energy consumption. [5]

Figure 8: PowerLogic PM800 with integrated display [5]

3.3.2. PowerLogic PM3255

PowerLogic PM3000 series is providing detailed accurate (accuracy class 0.5S) information about electrical distribution including instantaneous RMS values (current, voltage, power, etc.), energy consumption, demand values and power quality measures (THD). It is compliant with various standards including IEC 61557-12 (Electrical safety in low voltage distribution systems up to 1 000 V AC and 1 500 DC), IEC 62053-21/22 (Static meters for active energy) and IEC 62053-23 (Static meters for reactive energy). Energy consumption can be arranged in up to four different tariffs.

Figure 9: PowerLogic PM3255 [6]

In the factory PM3255 power meter is used, which is equipped with Modbus communication protocol using RS-485 interface, 2 digital inputs and 2 digital outputs. [6]

3.3.3. PowerLogic PM5560

PowerLogic PM 5560 is high-end power meter with highly precise measurements (up to class 0.2S) for energy metering and power quality analysis. PM5000 has non-volatile memory, which allows data logging of alarms, peak instantaneous values and phase identification.

Figure 10: PowerLogic PM5560 [7]

PowerLogic PM5560 is equipped with 2 Ethernet ports and one RS-485 port with Modbus TCP protocol. This meter is a great choice for energy metering in smart buildings, because it can communicate through BACnet protocol (Building Automation and Control Network). [7]

3.3.4. MasterPact with MicroLogic 5.0 P

Alternative to traditional energy metering is usage of control units for circuit breakers. For example, air circuit breaker MasterPact with mounted MicroLogic 5.0 P is used in the factory. Air circuit breaker protects lines from damage caused by equipment ground faults, overloads and short circuits. MicroLogic 5.0 P measures RMS values, calculates power and energy values. It supports alarm programming and logging with timestamps. [8]

Figure 11: MicroLogic 5.0 P [8]

3.3.5. Frequency drives

Nowadays, frequency drives often support communication with PLCs and they measure RMS values and active power. Therefore, frequency drives are perfect opportunity for power monitoring without power meters. An example is ACS580 drive from ABB, which supports various protocols (DeviceNet, PROFINET, Modbus and others) and provides access to configurable real-time data measurements. Power data may be processed later in PLCs. [9]

4. Communication

4.1. Open Systems Interconnection model

This model was introduced in year 1983 by International Standards Organisation as ISO 7498. It characterises and standardises the way how message is built and physically sent over from a transmitter device to a receiver. It is widely used in telecommunication and computing systems. The model is split into 7 specified layers. Each layer serves the layer above it and is served by the layer below it. The interface between each layer is predefined, therefore it is possible to set up a communication between devices developed by different vendors. [10]

4.1.1. Physical layer

The first layer of OSI conceptual model is a physical layer. It provides the mechanical, electrical, functional and procedural means for bit transmission between data link entities. Thus, it specifies a transmission medium (twisted pair cable, coaxial cable, optical fibre, etc.), transmission rates, voltages levels, timings of voltage changes, physical connectors and other specifications. [10], [11]

4.1.1.1. TIA/EIA 485

EIA/TIA 485 is a communication standard published by Telecommunication Industry Association and Electronic Industries Alliance. It uses differential signalling over twisted pair and provides data rates up to 10 Mbit/s. There can be up to 32 transmitters and 32 receivers connected to the same bus, which can be up to 1200 meters long. TIA/EIA 485 consists of two signals, which allow three different states – logical 1, logical 0 and deactivated transmitter. That is an important property, because it allows implementation of serial bus structure as shown in the picture below.

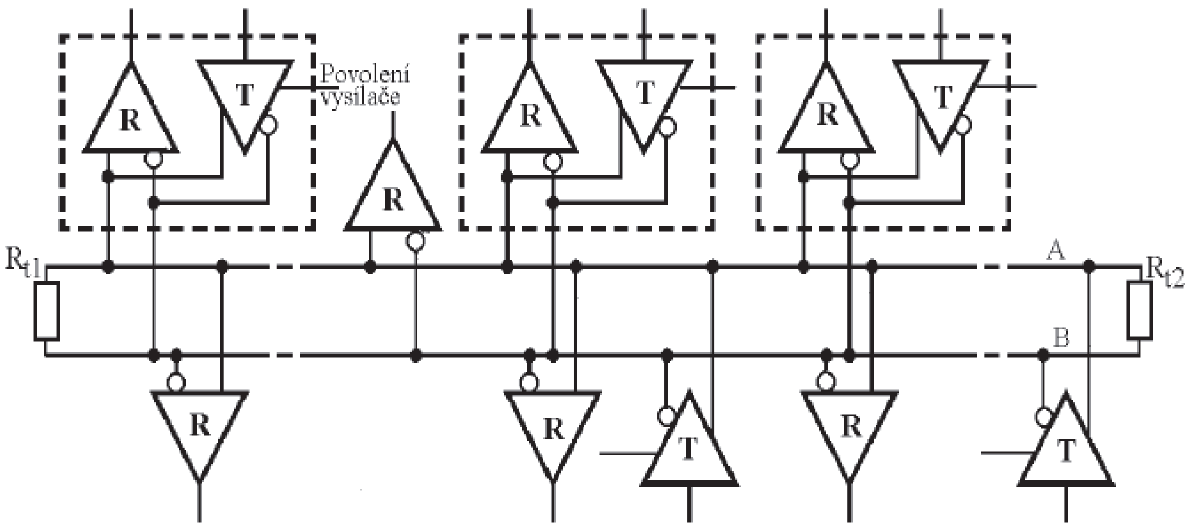

Figure 12: Serial bus realized via TIA/EIA 485 A [11]

4.1.1.2. TIA/EIA 568

This standard provides specifications for building a structured cabling system including standards for horizontal cables, interconnection equipment and defines a hierarchical cable system architecture via a star topology. The most well-known feature of TIA/EIA 568 is its eight-conductor 100-ohm balanced twisted pair cable. It uses various pinout connectors. One of them is RJ45, which is widely used for ethernet connection. Cables are divided into 7 categories and the higher category, the better cable in terms of data transmission rates. Category 5 is the base standard and has a bandwidth of 100 MHz, which can support all ethernet media systems.

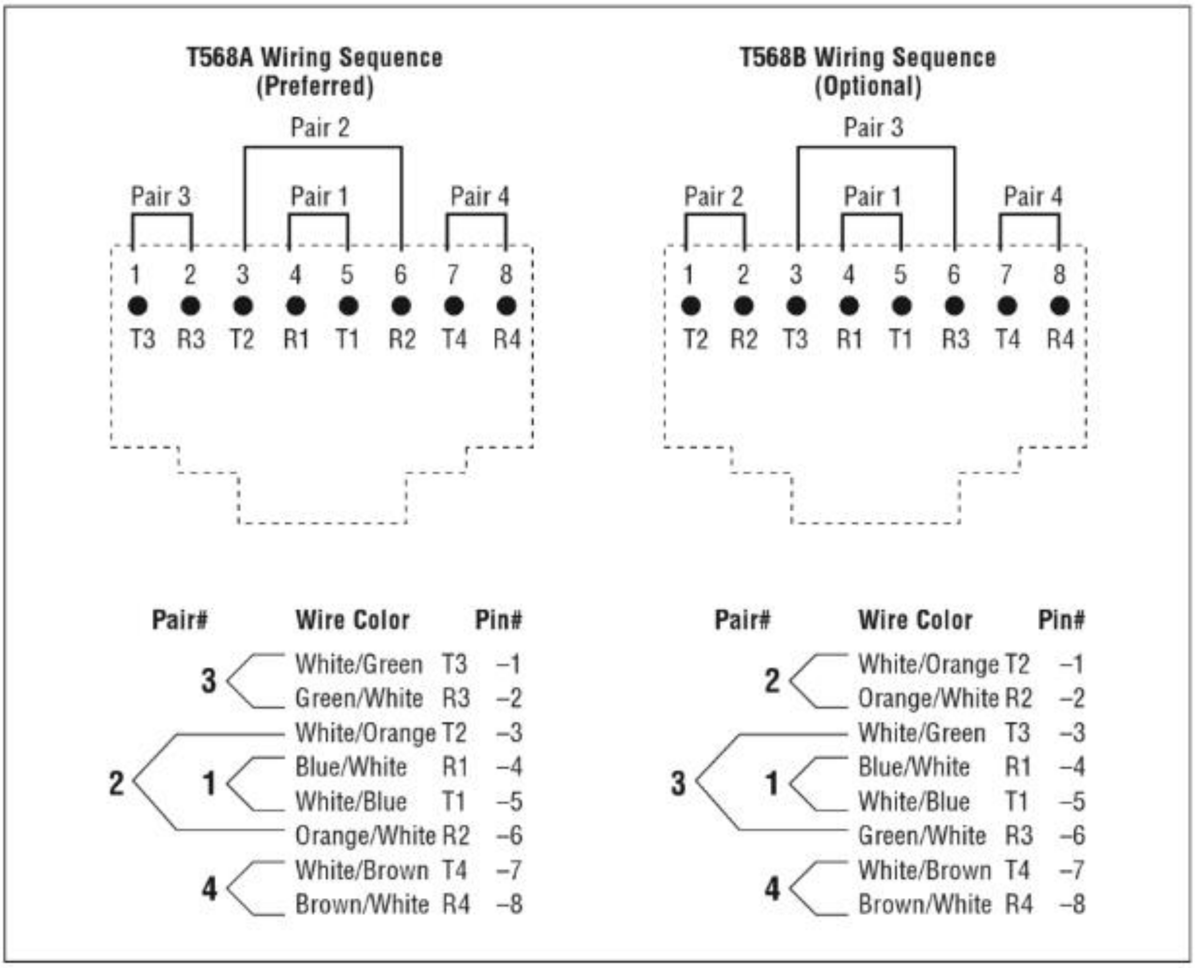

Figure 13: Wiring according to TIA/EIA 568 [12]

4.1.2. Data Link layer

The Data Link layer ensures errorless data chunk transfer. It establishes, maintains and releases data link connections with network entities. In order to serve its purpose, it frames the transferred data chunk with synchronization sequences, addresses and other functional components. In addition to framing it also performs data error detection and possibly even correction. The simplest error detection in the parity bit check (even, odd, space, mark). [11]

4.1.3. Network layer

The purpose of the network layer is to enable higher layers to communicate without knowing the network architecture, nor transfer characteristics. It is responsible for packet forwarding, finding and creating of the most optimal transmission communication route. The network layer issues requests to the data link layer and responds to the transport layer. Each network entity has a unique network address, which is used to identify each end of open systems. [11]

4.1.3.1. Internet protocol

The function of Internet Protocol (IP) is to deliver packets from source to destination based on the IP addresses. IP datagram is divided into a header, which contains source and destination IP address and other metadata, and payload, which contains transmitted data. [13]

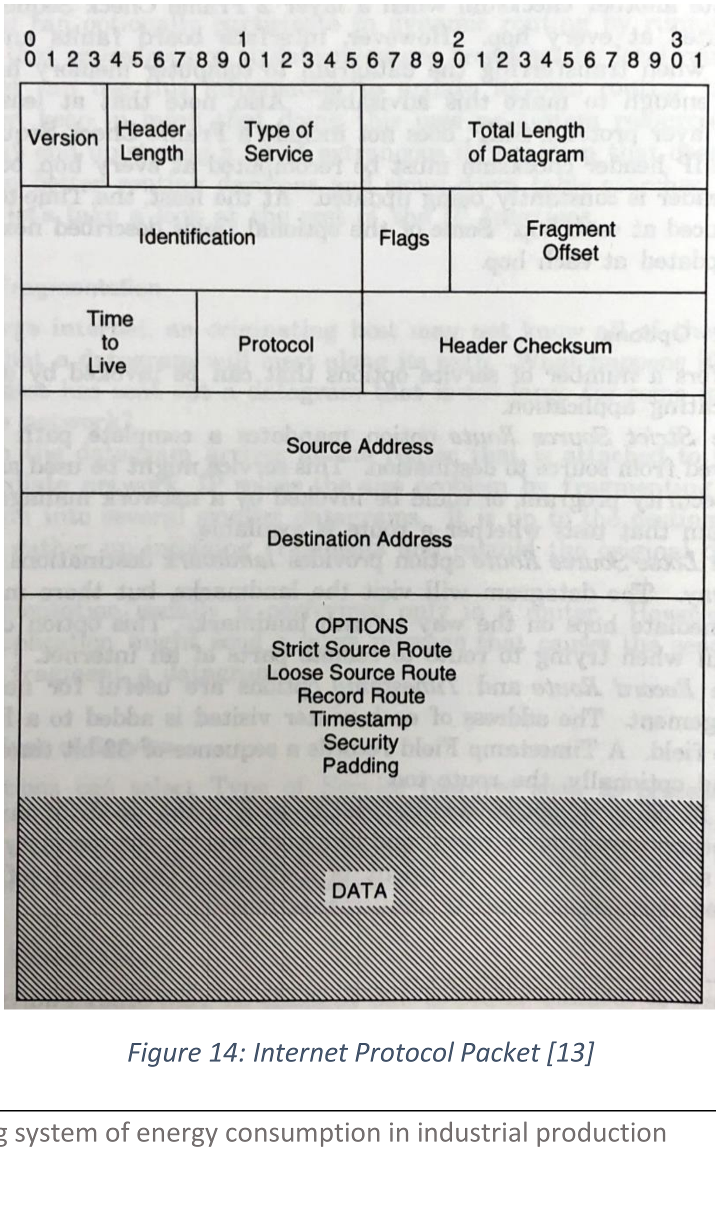

Figure 14: Internet Protocol Packet [13]

4.1.4. Transport layer

The fourth layer, the transport layer, controls and manages the lower layers. It ensures reliable data transmission in the right order without data loss, duplication and redundancy. The protocols of transport layer enable simultaneous host-to-host communication services for multiple applications within one computer in a network. It breaks and rebuilds data into ordered packets and controls the rate of data transmission to prevent transmission of more data than can be supported. [11]

4.1.4.1. Transmission Control Protocol

One of the most important communication protocols is called Transmission Control Protocol (TCP). It operates in a client/server environment. A server always listens for possible incoming connection requests from client. The function of TCP is to assure that data is delivered reliably, in sequence and without any errors. It is realized through predefined routine of handshakes, encryption key exchanges, positive acknowledgments and connection terminations. Each TCP connection is numbered, therefore it can ensure, that every packet arrives in the correct order. The size of each packet can be up to 100 bytes. [13]

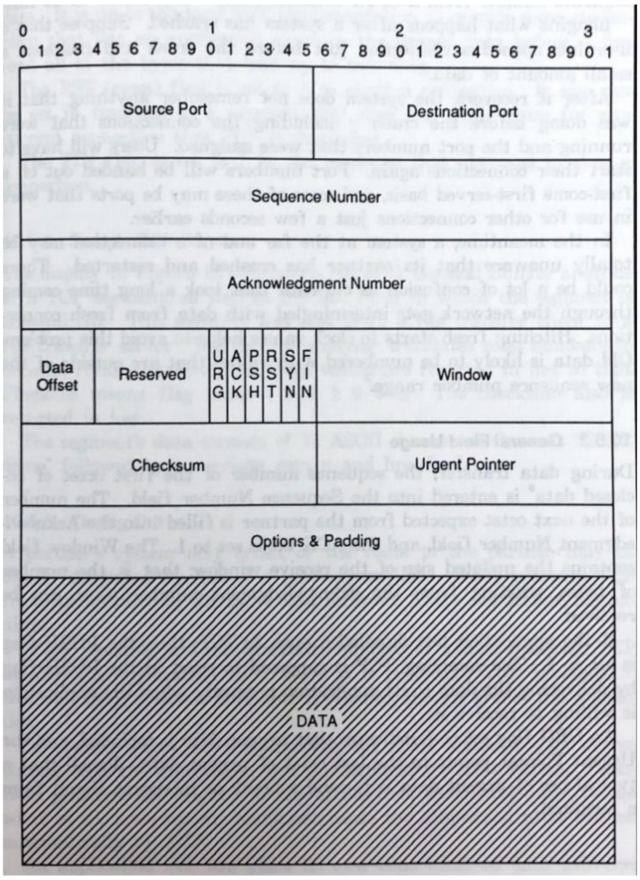

Figure 15: TCP segment [13]

4.1.5. Session layer

The session layer provides the means necessary for cooperating presentation entities to organize and synchronize their dialogue and to manage their data exchange. It provides services to establish, maintain, synchronize and terminate communication sessions between two presentation entities in an orderly manner. [11]

4.1.6. Presentation layer

The purpose of the presentation layer is to ensure that the data from application layer are preserved during data transmission. It is responsible for code transformations, data format, compression and encryption and decryption. Probably the most well-known presentation layer protocol in HyperText Transfer Protocol (HTTP) or its newer version HyperText Transfer Protocol Secure (HTTPS), which in addition to HTTP includes encryption and decryption. [11]

4.1.7. Application layer

The application layer is the highest layer of the OSI model; therefore, it must provide all services directly usable by application processes. It directly interacts with software applications with a communicating component. It contains all communication functions which are not already performed by the lower layers. [11]

4.1.7.1. Modbus application protocol

Modbus was introduced in 1979 by Schneider Electric, former Modicon company, and it is still preferred option until today. Modbus application protocol works as a client/server communication between devices connected on various types of networks. It is a request/reply protocol with services specified in function code, which is part of 253 bytes long protocol data unit (PDU). Mapping of Modbus on network or specific buses introduces some additional layers on the application data unit (ADU).

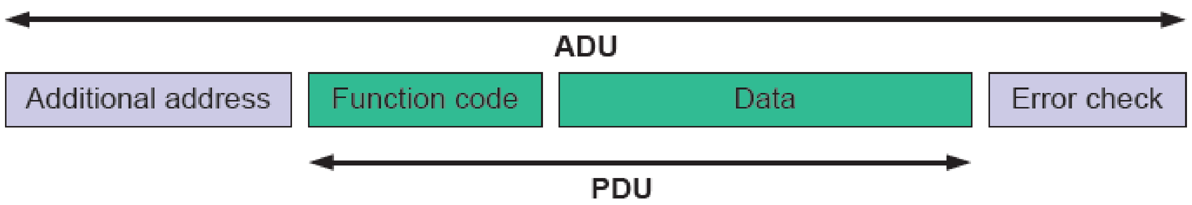

Figure 16: Modbus data frame [14]

As Modbus is an open protocol, every type of device can use it. In the factory Modbus is used in 2 different network types. One, where meters are connected to a gateway via TIA/EIA 485 bus, and the other one, where meters are connected to Modicon PLC via

TIA/EIA 568 using TCP/IP (port 502). The whole Modbus architecture in the factory is very similar to an example in the picture below.

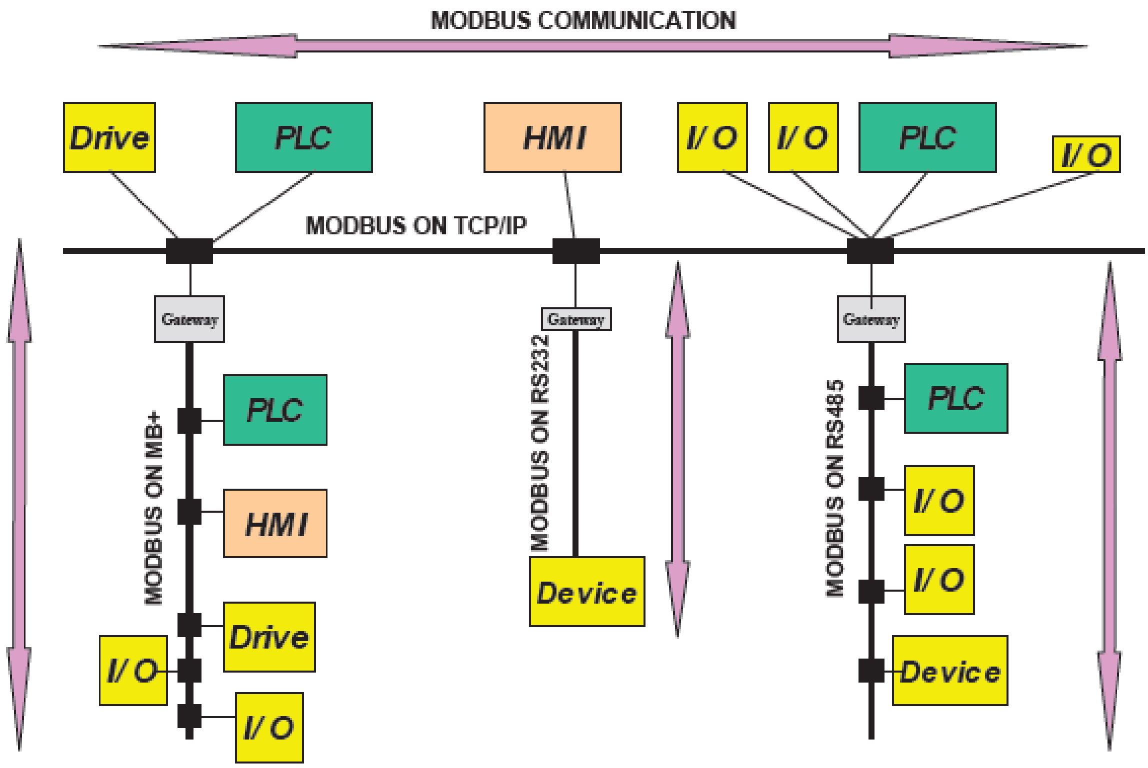

Figure 17: Modbus network architecture [14]

The communication over TIA/EIA 485 can be described as a model master/slave, where a gateway is a master, who manages the communication with other devices and it becomes a communication hub, and all the other devices act as slaves waiting for requests from the master. [14]

4.1.7.2. Communication Industrial Protocol

Communication Industrial Protocol (CIP) is an open industrial protocol supported by Open DeviceNet Vendors Association (ODVA). It includes set of messages and services supporting control, safety, energy, movement, configuration and information applications in the industrial automation. It is used by EtherNet/IP, CompoNet, ControlNet, DeviceNet and other industrial network architectures.

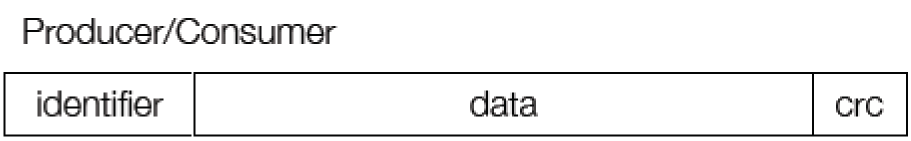

Figure 18: Producer/Consumer model [15]

CIP uses Producer/Consumer messaging scheme instead of traditional Client/Server model. Producer is a device, which produces a message and puts it on the network for consumers. It is not directed to any specific consumer. Consumer picks up messages on the network, which has been placed by a producer. [15]

4.2. EtherNet/IP

EtherNet/IP is a common industrial network architecture, which unlike other traditional fieldbus architectures uses ethernet standards (TIA/EIA 568 physical layer and TCP/IP protocols). It is completely open network for any vendor with full range of manufacturing applications. With introduction of EtherNet/IP, there is virtually unlimited total network distance, but network management tools may be needed compared to fieldbus networks. It supports various protocols such as Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP), Simple Network Management Protocol (SNMP) and others. On the other hand, EtherNet/IP brings cyber security issues. [16]

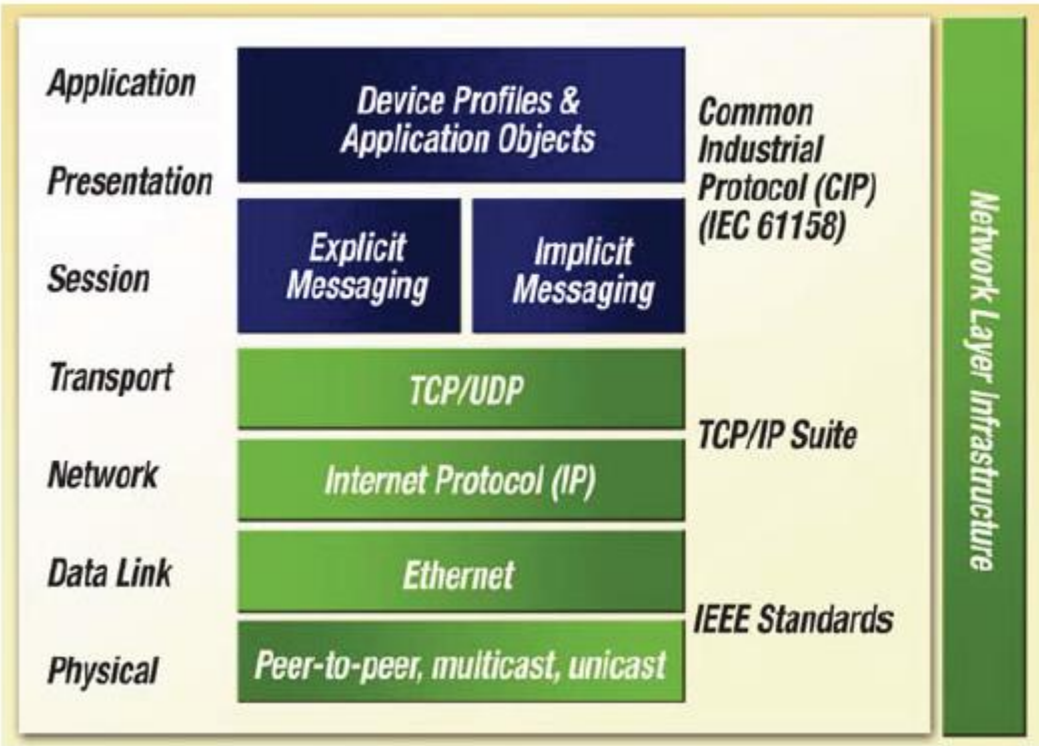

Figure 19: EtherNet/IP relation to OSI reference model [16]

5. Data storage systems

One way to store data is to use operating system file. The biggest advantage of file system is its invisibility and simplicity. Users are usually not even aware of it and naturally know how to use it. The major disadvantages are:

1) Data redundancy and inconsistency

Some data may be duplicated as the data for different applications or departments within a factory are usually stored in different files. Some employees can be part of two departments, which might result in copying the same data into 2 files. This leads into higher storage cost and possible inconsistency, as the data regarding one employee can be updated in one file but not in the other one.

2) Accessing the data

The data stored in files is usually structurally designed to satisfy predefined request, but other requests might arise later. This means, that new application programs must be written by a programmer, which causes problems and slows the projects down.

3) Data isolation

As the data are distributed within various files, which can be in different formats, it can be difficult to write new application programs to retrieve wanted data.

4) Atomicity

In order to create safe application, it is necessary, that data transactions are either committed fully without any errors or they do not happen at all. In conventional file systems, it is possible to ensure atomicity, but it is very difficult.

5) Security

Usually not every user should have the right to access various files, due to confidentiality. Applications are added in ad hoc manner, which makes it difficult to ensure all security constraints.

The other way to store data is to use database systems. “A database system is a collection of interrelated data and a set of programs that allow users to access and modify these data.” The data is stored in predefined structure, which prevents data redundancy and inconsistency. A database usually consist of many tables and the user access to these tables can be managed by a database administrator. [17]

5.1. Relational database

The relational database model is the most used data model for commercial use. The main advantage is the ease of use for programmers and users compared to other data models. Relation database consists of tables with unique names. These tables are made of rows (tuples) and columns (attributes). Tables of the database are designed in a way so that various relations between attributes and tuples can be found. [17]

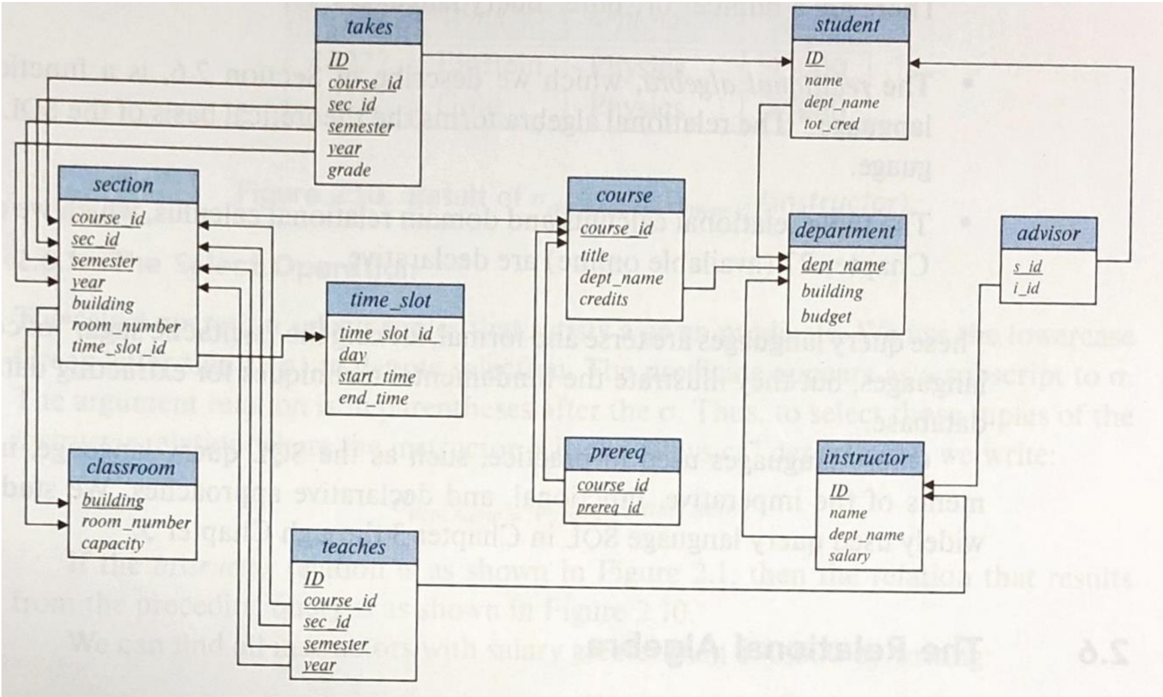

Figure 20: Relational database schema diagram [17]

5.1.1. Structured Query Language (SQL)

SQL has been developed by IBM in early 1970s. It is the most used query language for relational databases. It has been even standardized by the American National Standards Institute (ANSI) and the International Organization for Standardization (ISO). SQL language can define the data structure (create and edit tables), modify data (add, remove and modify tuples), query a database and specify security constraints.

SQL supports variety of basic data types such as char (a fixed-length string), varchar (a variable-length string), int (an integer number), smallint (a small integer), numeric (a fixed-point number), real (a floating-point number) and float (a floating-point number with predefined precision). [17]

5.2. Big Data storage systems

In order to store big chunks of data, relational databases might not be the fastest option. New data management systems were developed to satisfy the need to collect data in real time not only from sensors and other IoT device, but also from websites, social media and search engines. Big Data vary from relational databases mainly based on these metrics:

1) Volume

Big Data systems process and store much larger data sets than relational databases.

2) Velocity

The data entry rate into Big Data storage systems is near to real-time and most of the applications need the data to be available as soon as possible in order to respond quickly.

3) Variety

Nowadays, there are many sources of data, which can be expressed in other than relational form (such as textual data, graph data or semi-structured data). [17]

5.2.1. Distributed file system

Files are broken up into multiple blocks, which are stored across several machines. These blocks are replicated to more than one machine (usually at least three) to ensure the data availability. The client does not need to know where physically the file is stored as this is managed by the system. A good representatives of distributed file systems are Google File System (GFS) and Hadoop File System (HDFS), which was derived from GFS. [17]

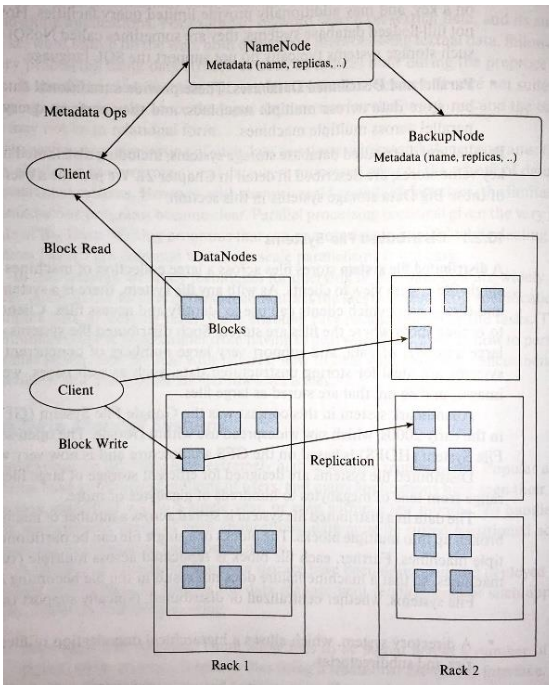

Figure 21: Hadoop File System architecture [17]

5.2.2. Sharding

The data is partitioned across multiple databases. Partitioning is usually done with partitioning key. The key is used to define partitioning rule based on predefined range of that key. The client's software needs to keep track of where the required data is and send appropriate query to each database. An example of Sharding system is MySQL Cluster, which has an auto-sharding function. [17]

5.2.3. Key-Value storage systems

Key-Value storage systems provide a way to store values with associated keys from thousands of devices or machines. They can be partitioned and replicated to multiple machines. Two basic functions of the systems are put(key, value), used to store the value, and get(key), used to retrieve the value. As Key-Value systems did not usually support any form of SQL queries they are referred to as NoSQL systems, but later it became obvious, that the lack of any form of SQL makes it more difficult to implement such systems. Later each data entry has been equipped with timestamp or alternatively with integer that is incremented with every data entry.

Key-Value systems can handle large amount of data queries and large amount of data records thanks to division of load between many machines. Operational Historians are usually based on Key-Value storage systems. [17]

5.2.4. Parallel and Distributed databases

The system runs databases on multiple machines, which run in parallel and is referred to as cluster. The data is replicated across cluster in order to process large amount of queries and to ensure no data loss. This increases the potential to a failure during execution a query. The way these systems deal with query failure is simply by restarting the query once again.

While interacting with parallel databases, the user does not see a difference as they are equipped with the same interface as traditional databases. [17]

6. Data visualization

The goal of data visualization is to generate reports from a database, which can be easily readable from human perspective. They query a database in predefined way in order to get the data in a particular form and then create tables, charts or simply format a text.

6.1. Tableau

Tableau is a business analytics platform for graph-type data visualizations. In year 2008 Tableau has been awarded a prize for “Best Business Intelligence or Knowledge Management Solution” by The Software & Information Industry Association. [18] The whole platform of products consists of:

1) Tableau Desktop (Both professional and personal editions)
2) Tableau Prep
3) Tableau Server
4) Tableau Online
5) Tableau Data Management
6) Tableau Server Management
7) Tableau Mobile

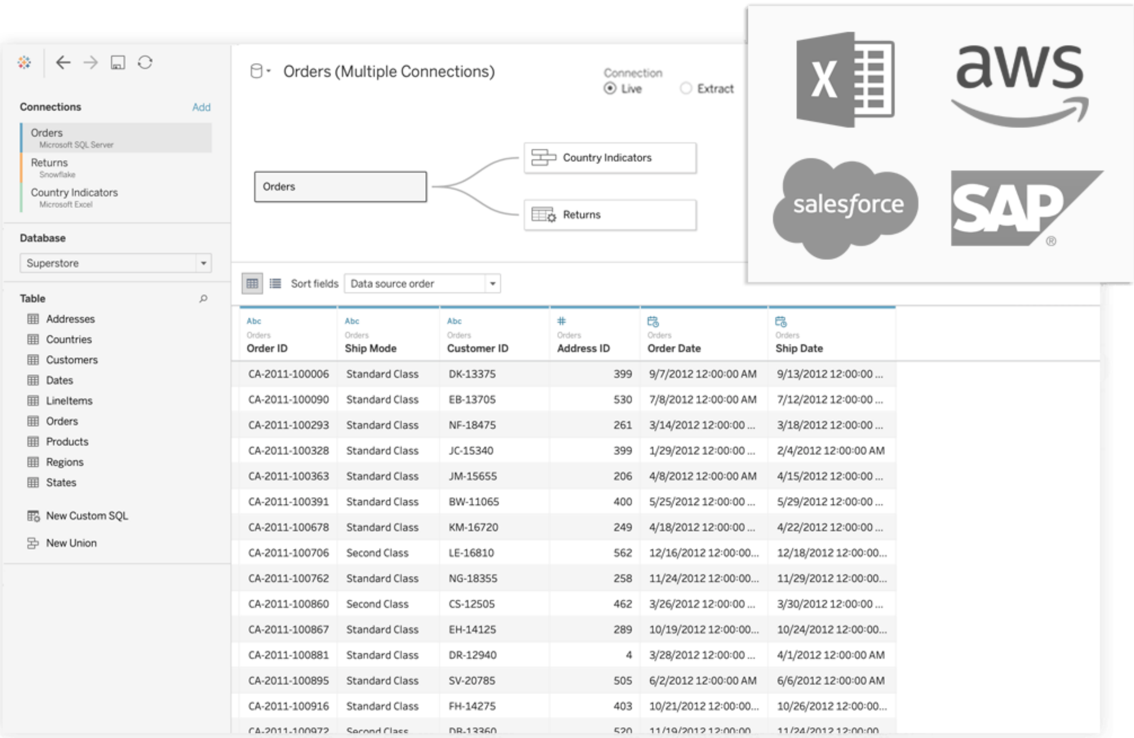

Figure 22: Tableau Desktop [19]

The data source for Tableau can be Excel spreadsheets, cloud databases, Hadoop databases, relational databases or many others. It can also download, store a retrieve the data within its memory. [19]

6.2. ThingWorx

ThingWorx is an Industrial Internet of Things (IIoT) platform that helps to connect employees with process. One can connect to and visualize SQL or cloud database or directly an IoT device. The platform serves as an interface for the developer to create dashboards full of graphs, that can be used a portal for important data for production morning meetings, or user interfaces for remote production control.

ThingWorx comes with a set of pre-built applications for faster implementation within a factory. Controls Advisor is an example of a pre-built application, that can read PLC tags through OPC servers, save the data, create trends and alarm, when the value is out of limit or the communication is not working. [20]

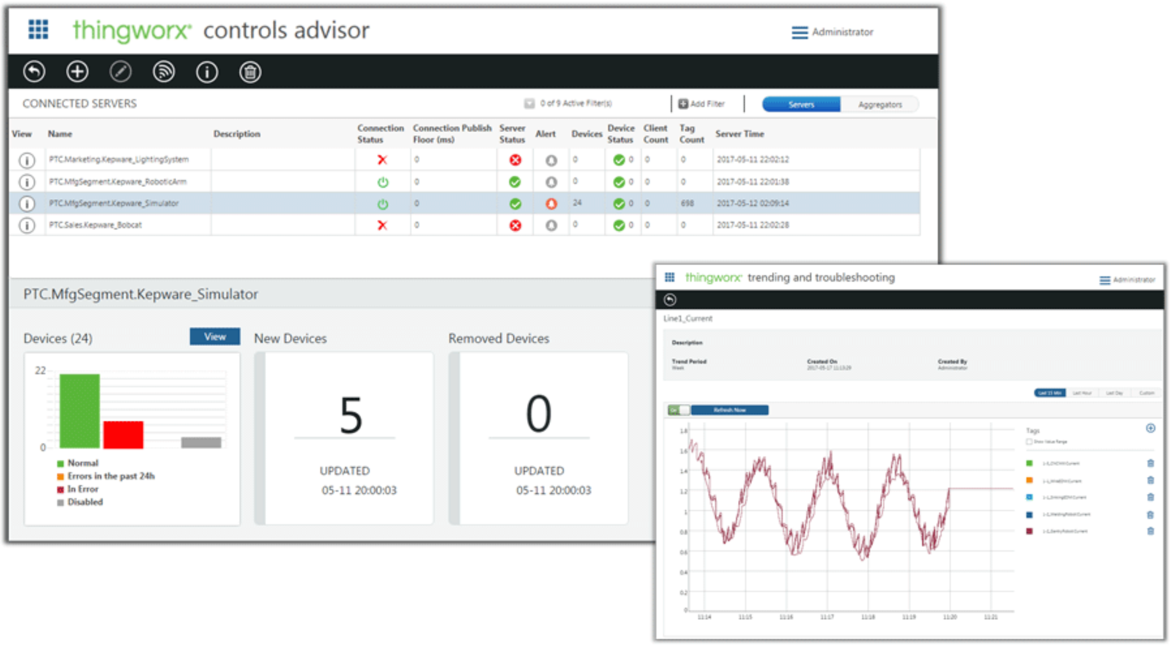

Figure 23: ThingWorx Control Advisor [20]

ThingWorx has a library of many widgets, that can for example display the level of material in a tank or they can serve as control button or scroll bar for the operators. All visualizations can be coded with Javascript programming language. That allows developers to create anything they need without any limitations. [20]

Compared to Tableau or Power BI, ThingWorx is not just a tool for data analysis, but it can be used to create user interfaces with control elements, dashboards, where a user can actually change some values, or just as an easy visualisation of a table in database, where a user can add or delete rows.

6.3. Power BI

Platform developed by Microsoft, which is a leader in Analytics and Business Intelligence. That is how Power BI can be described. It can be easily connected with Excel, CSV, SQL and cloud databases and possibly any form of data. It works as a desktop application, which is free of charge for individual users, but if the reports are shared, premium version is needed. Reports can be published onto a cloud Power BI solution and later shared with other users.

In Power BI, developers can use Data analytics expressions (DAX) to create new data metrics. DAX is a form of query language used in Excel to use Power Pivot feature to analyse the data stored in Excel.

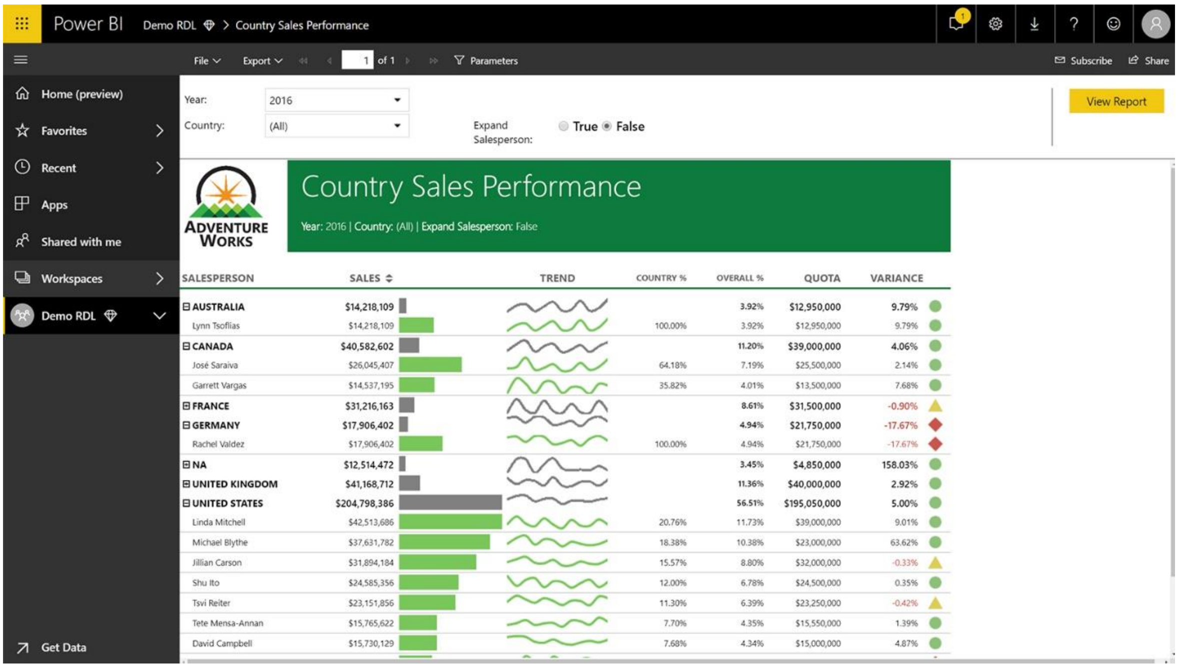

Figure 24: Country Sales Performance report in Power BI [21]

Power BI is a standard visualization platform used in big corporate companies. These visualizations can be built to be viewed in web browser on any PC or using a mobile device. All data is stored in the cloud protected with Microsoft Information Protection. Cyber security of business sensitive data is a key and needed requirement for any visualization solution. [21]

6.4. DataWrapper

DataWrapper is a German open source platform that is in the basic form free to use. One can upload an Excel sheet, comma separated file or link a Google Sheet as a source dataset. If a Google Sheet is linked, the desired visualization is going to be live. Then a user needs to select desired chart, map or table and customize it into a desired output. DataWrapper generates a link hosted on their server, which can be used to share the visualization.

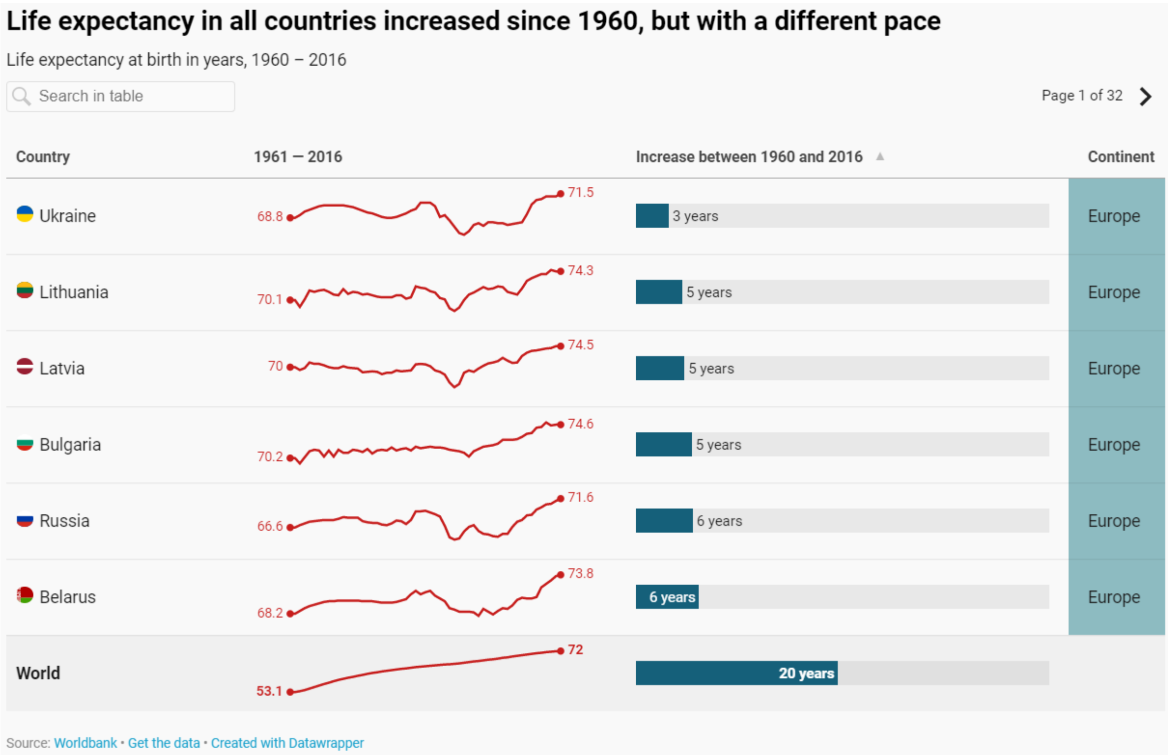

Figure 25: Life expentancy list made in DataWrapper [22]

DataWrapper is a popular choice by many journalists such as The New York Times, WIRED and Fortune. It could definitely be used in industrial production as well for quick data analysis, because its simplicity and ease of use. It can also support fully customized solutions, where the data would be secured and private, but that doesn't comply with the idea of standardization. [22]

CHAPTER 2

7. Monitoring System Design

At the beginning of each project, the most important phase is to map existing solutions within the factory and then precisely describe what needs to be achieved.

7.1. Power Monitoring Expert

In the factory there was a monitoring system called Power Monitoring Expert (PME) developed by Schneider Electric. It is a digitalization solution, which helps to visualize the overview of the whole power network of the factory. PME can be used for water, compressed air, gas, electricity and steam (WAGES). Power, energy and flow meters from Schneider Electric can be easily added into the system.

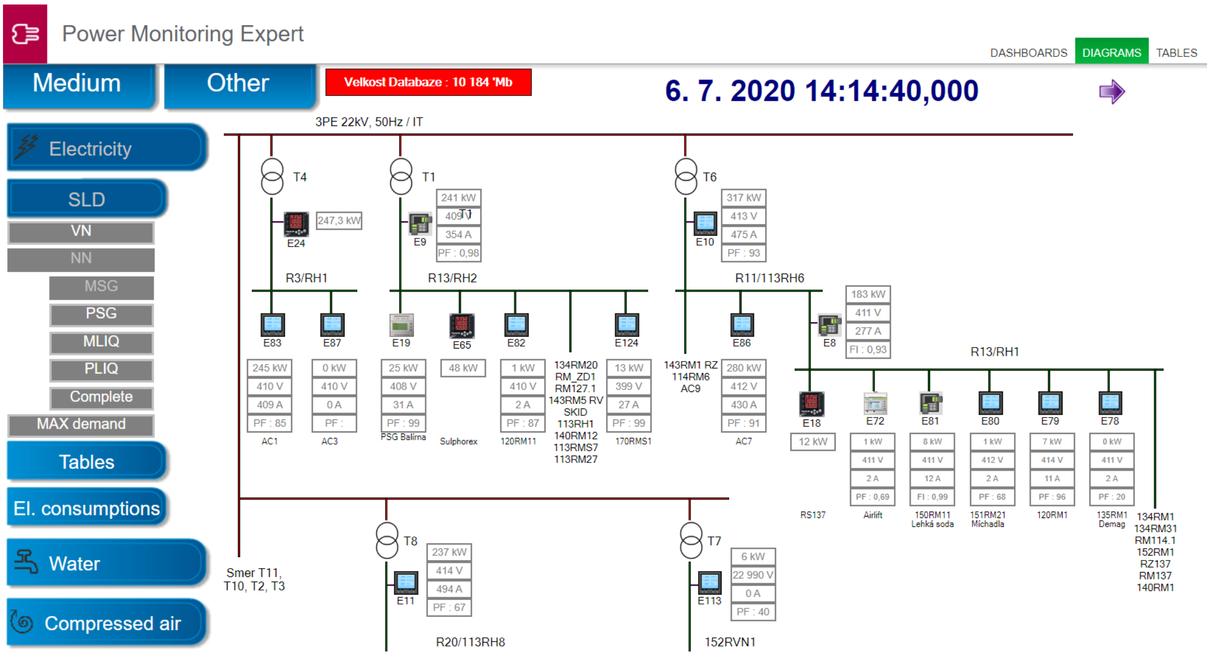

Figure 26: Power Monitoring Expert - Power Network

The system provides detailed information about power quality and energy usage. In the first chapter I mentioned a few important cost factors such as Total Harmonic Distortion feedback (THD), peak power demand and power factor limitation, which are monitored through PME. It serves as a gate between an electrician technician, who is responsible for the power quality, and all the power meters across the factory.

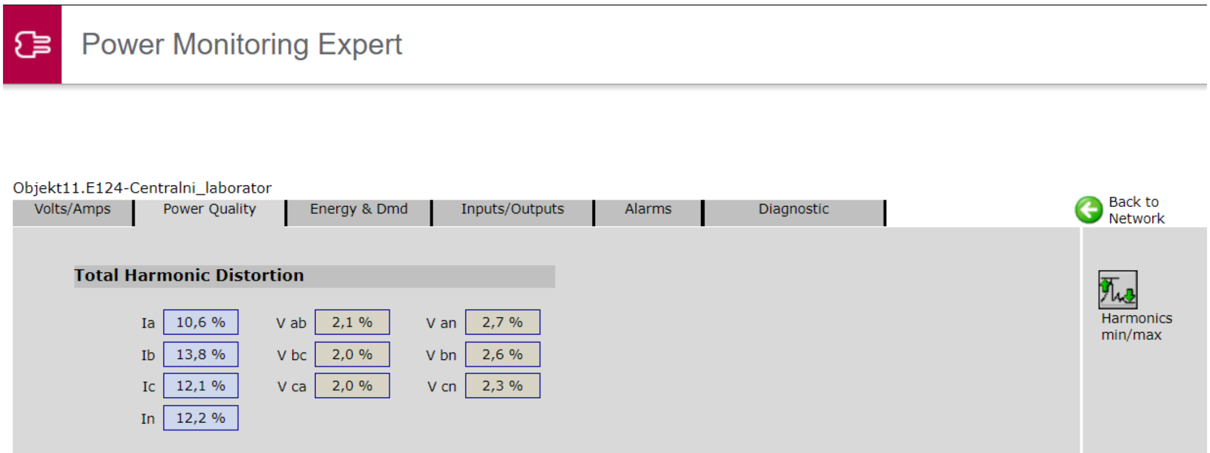

Figure 27: Power Monitoring Expert - Detailed information

The system has its own SQL database to store historical data. It can be used to view various trends and to automatically generate predefined reports. A user can save their settings to load desired report without the need to choose the parameters.

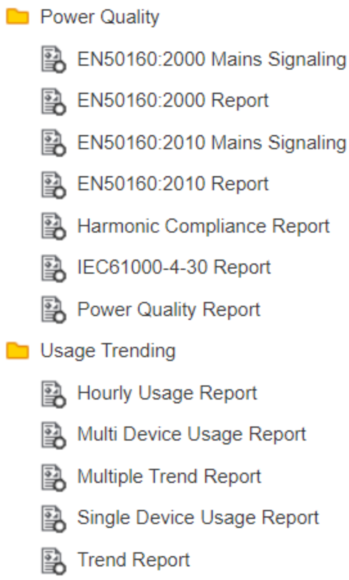

Figure 28: Power Monitoring Expert - Reports

Even though PME is a great tool for power network administrators, there is still room for improvement. It is not easy to use for process technicians and engineers due to the time required to load each report and absence of connection to the actual production runs nor any production values. That is why the data is used only on plant level, but not within departments in the factory, where there might still be significant energy leakages such as powerful compressors, which are turned on even though there was no production at that time.

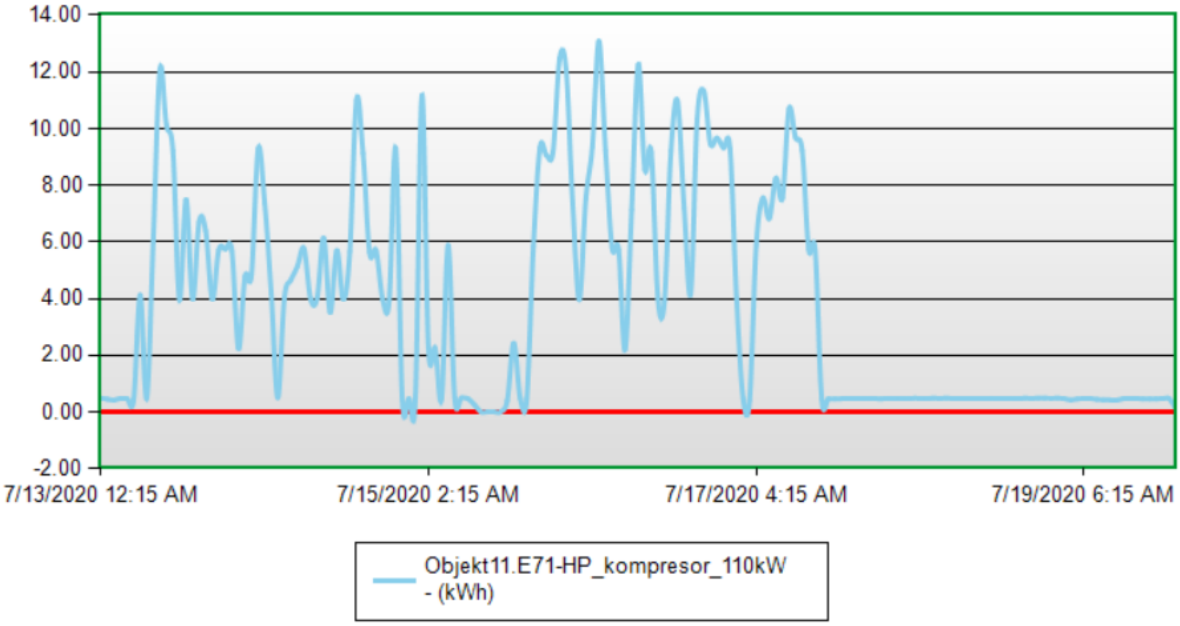

Figure 29: Power Monitoring Expert - Hourly usage report

7.2. Report design

After an analysis of existing solution, it was needed to design the whole new energy monitoring system. The goal was to provide useful data for process technicians and management, who should be easy to analyse and improve on the current system. The process technician must see energy consumption and active power on daily basis and analyse it on run level. Management needs to be able to easily analyse daily, weekly and monthly results of energy spending and evaluate if there were any energy leakages, which could be minimized.

The factory is split similarly as described previously with one addition and that is operation, because it serves to more than one business unit of the whole corporate company. In one operation, there are usually making and packing departments, which are divided into process units or simply production lines.

I have decided to split the reporting system into three kinds of reports:

1) Compliance report
2) Batch report
3) Overview report

The compliance report shall be just a simple table, that interprets if all the targets were met the previous day. The process technician needs to be able to immediately say, if they need to devote some of their time to energy spending or not.

The batch report is where the process technician is redirected from the compliance report. It displays the active power of each device throughout individual run. It needs to be able to show the data with perspective to the line status.

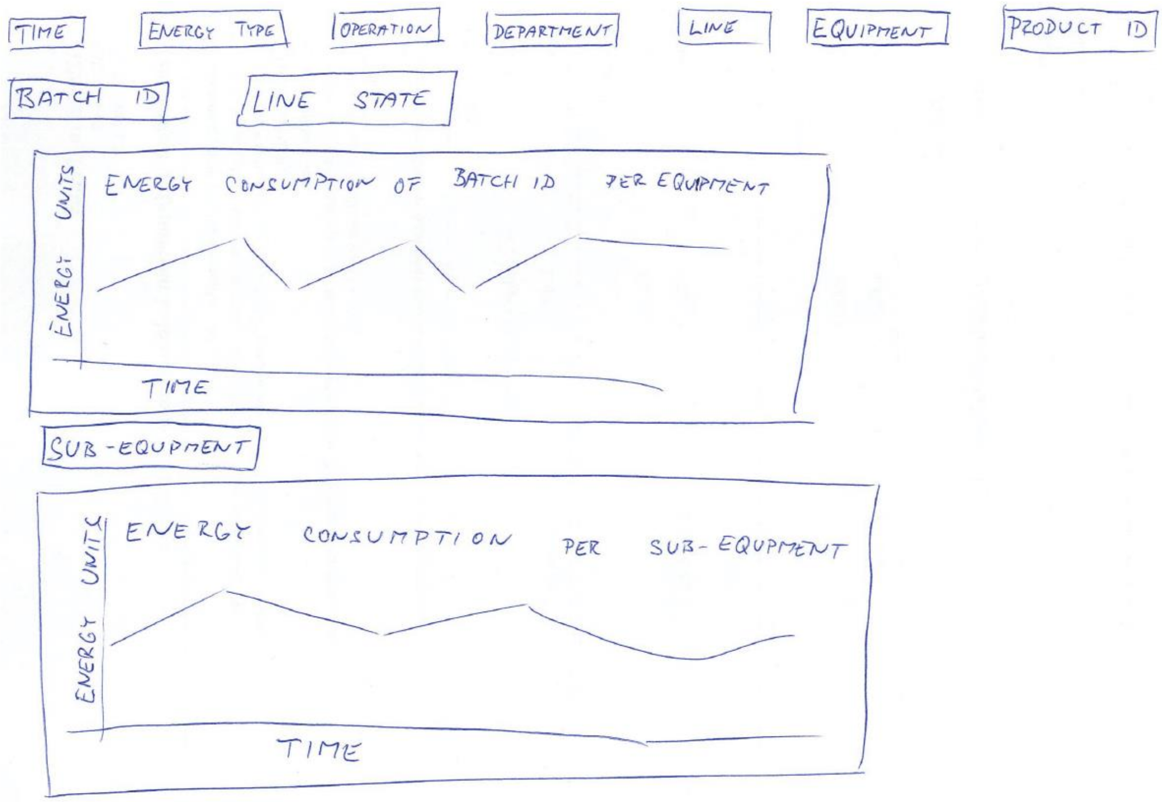

Figure 30: Batch report design

The overview reports should serve both to management and process technicians to give insight of energy spending in bigger perspective. They should review trends on weekly and monthly basis.

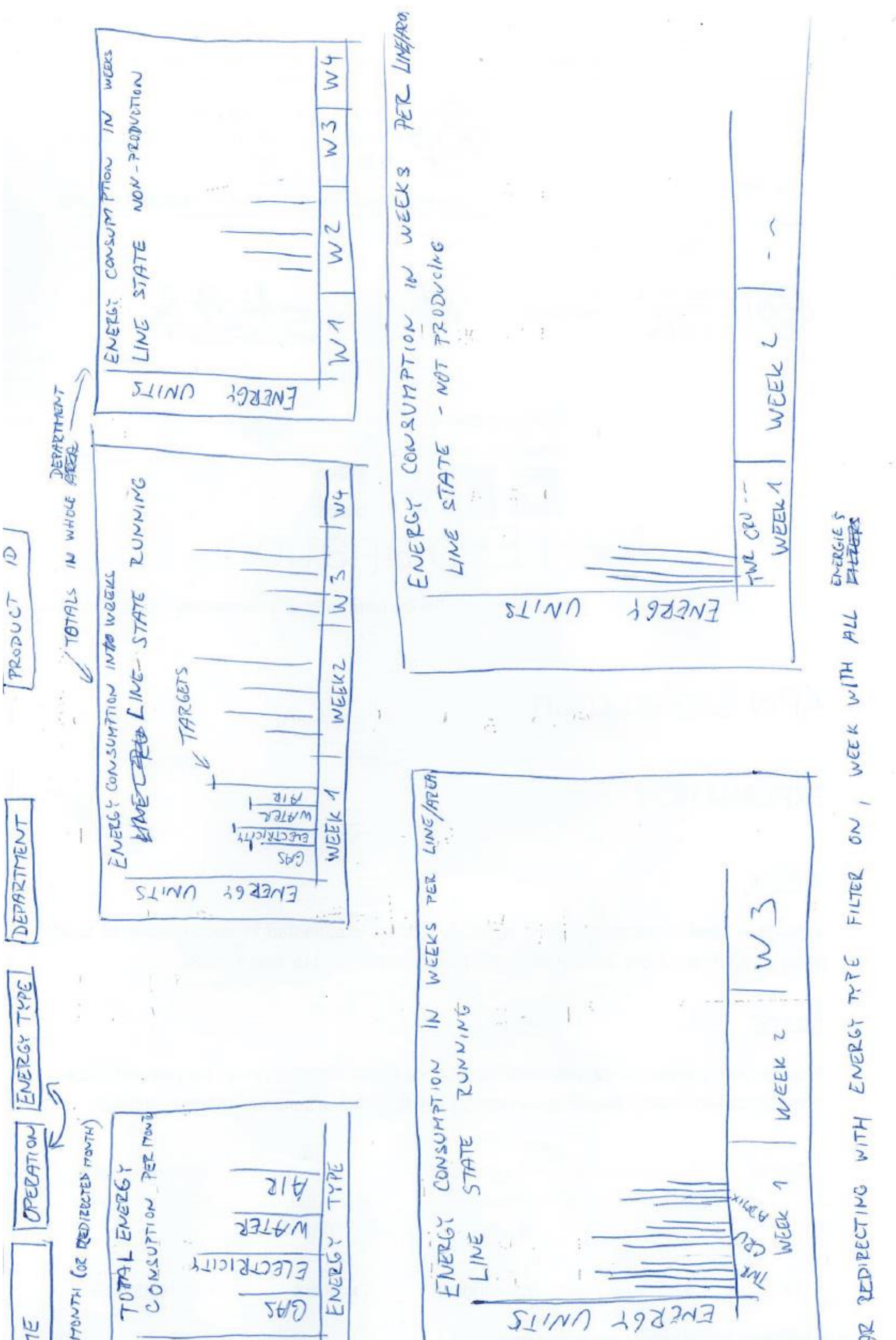

Figure 31: Overview report design

8. Communication and data structure

At the beginning of every digitalization project it is necessary to ensure the flow of data and setup the architecture of the whole system. Therefore, it was needed to map all available meters and setup the communication route to production historian.

8.1. Power Meters mapping

Initially I found out, that in the factory, there are fundamentally two types of energy meters in terms of communication:

1) Meters with pulse output

Flowmeters are usually meters with pulse output. They are usually connected with PLC (in my case Modicon M258) and there is predefined constant of how many units of energy one pulse means. For example, one pulse of electricity meter might mean 5 kWh.

2) Meters with serial communication interface

These meters are connected to a gateway. It acts as a master, which manages the communication and serves as an access portal for other devices that need data from energy meters with communication interface.

8.1.1. Modicon M258

Modicon M258 is a PLC developed and produced by Schneider Electric. By default, it has Ethernet and TIA/EIA 486 interface, therefore it is friendly to use with all sorts of energy meters and other devices. It supports various communication protocols such as Modbus TCP/IP, Master/Slave Modbus ASCII/RTU using serial port and Profibus. All pulse meters in the department are connected to this PLC. Energy totalizer tags are created in the PLC, which are continuously being incremented.

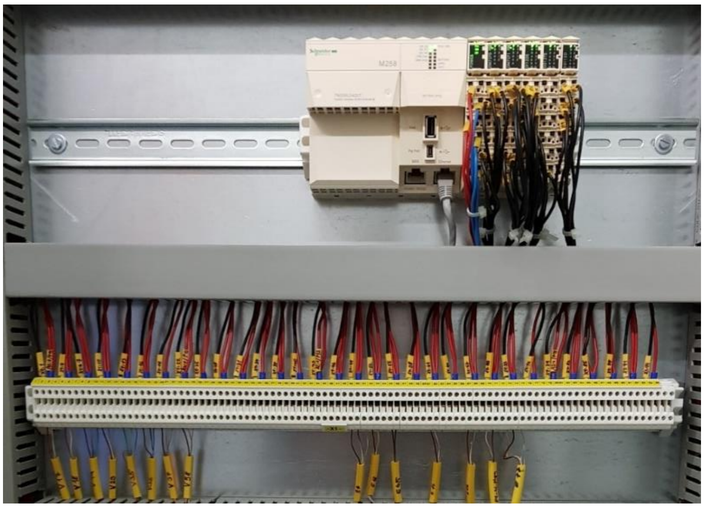

Figure 32: Modicon M258

8.1.2. Gateway EGX100

Meters with serial communication interface (e.g. PM800) do not require connection to any PLC as they provide complete information about the medium, they are measuring. A master device is required, which manages the communication with multiple slave energy meters. Gateway EGX100 serves as an access point to energy meters. Each meter has its device number, which must be specified in the request. Gateway translates the communication protocol from Modbus on TIA/EIA 486 to Modbus TCP/IP.

Figure 33: EGX100

Gateway EGX100 has a web interface through which one can easily access desired registers in each device connected to it. In Figure 34: Power registers for PM800 there is an example of a table with available registers for PowerMeter 800.

[1140] 1Second Metering – Power

Reg	Name	Size	Type	Access	NV	Scale	Units	Range	Notes	810	820	850	870
1140	Real Power, Phase A	1	Integer	RO	N	F	kW/Scale	-32,767 – 32,767 (-32,768 if N/A)	Real Power (PA) 4-wire systems and system types 10, 11, and 12	Y P	Y P	Y P	Y P
1141	Real Power, Phase B	1	Integer	RO	N	F	kW/Scale	-32,767 – 32,767 (-32,768 if N/A)	Real Power (PB) 4-wire systems and system type 12	Y P	Y P	Y P	Y P
1142	Real Power, Phase C	1	Integer	RO	N	F	kW/Scale	-32,767 – 32,767 (-32,768 if N/A)	Real Power (PC) 4-wire systems only	Y P	Y P	Y P	Y P
1143	Real Power, Total	1	Integer	RO	N	F	kW/Scale	-32,767 – 32,767	4-wire system = PA+PB+PC 3-wire system = 3-Phase real power System type 12 = PA + PB System 10, 11 = PA	Y P	Y P	Y P	Y P

Figure 34: Power registers for PM800 [23]

8.2. Data Types

Prior to sending the data back and forth, it is necessary to predefine correct data type in the receiving device, which is used for the data representation.

8.2.1. Integer

Depending on the number of words being communicated, signed integer can represent numbers in range of -32 767 ÷ +32 767 (one word which two bytes) or -2 147 483 648 ÷ +2 147 483 647 (two words, which is four bytes). The first bit indicates the sign and the remaining bits represent the number.

8.2.2. Float32

Float32 is four bytes communicated through 2 words, which interprets decimal numbers. The first bit is a sign, following 8 bits represent an exponent and the last 23 bits represent the fraction. Interpreted value can be calculated as:

$$value = (-1)^{sign} \cdot 2^{exponent-127} \cdot 1.fraction$$

8.2.3. Mod10

Mod10 can be signed and unsigned data type and depending on the size of the message it can vary in its range. In the register list for PowerMeter 800 Mod10 is used as unsigned four words data type. Each word represents four-digit positive number. The final encoded value can be calculated as follows:

$$value = R4 \cdot 10^3 + R3 \cdot 10^2 + R2 \cdot 10^1 + R1 \cdot 10^0$$

Where R1 to R4 represent integer value stored registers in consecutive order (R1 being the lowest register and R4 the largest one). [24]

8.3. Data Architecture

Data architecture can be described from information technology (IT) and operation technology (OT) point of view. All the data from OT is collected to production historian, which is the first element of IT.

8.3.1. Production Historian

In order to collect operational data Historian from Wonderware is used in the factory. It is highly effective relation database working in real time. Historian collects data from PLCs through an OPC server with minimal 1 second sample period. One can access Historian similarly as normal SQL server. Automated data collection of any PLC tag must be manually set up using ArchestrA System Management Console. There are different data acquisition methods used such as cyclic (stores data every predefined period) and delta (stores data with every change).

8.3.2. Data Flow Architecture

Power and energy consumption data is transmitted using Modbus on TIA/EIA 486 protocol to either EGX100 or Modicon M258. There the data is translated to protocol Modbus TCP/IP, which was supposed to be read from production Historian. Unfortunately, I was unable to setup the communication between Wonderware Historian and EGX100 and Modicon M258, therefore I had to search for another solution. One was to use one more gateway (for example Anybus X-Gateway), which would translate the data into Ethernet TCP/IP protocol, or another PLC. I chose PLC Micro850, because it was able to communicate using both Modbus TCP/IP and Ethernet TCP/IP protocols, that was necessary to set up using Wonderware OPC, and it was cheaper and faster option, because there was one available in the factory.

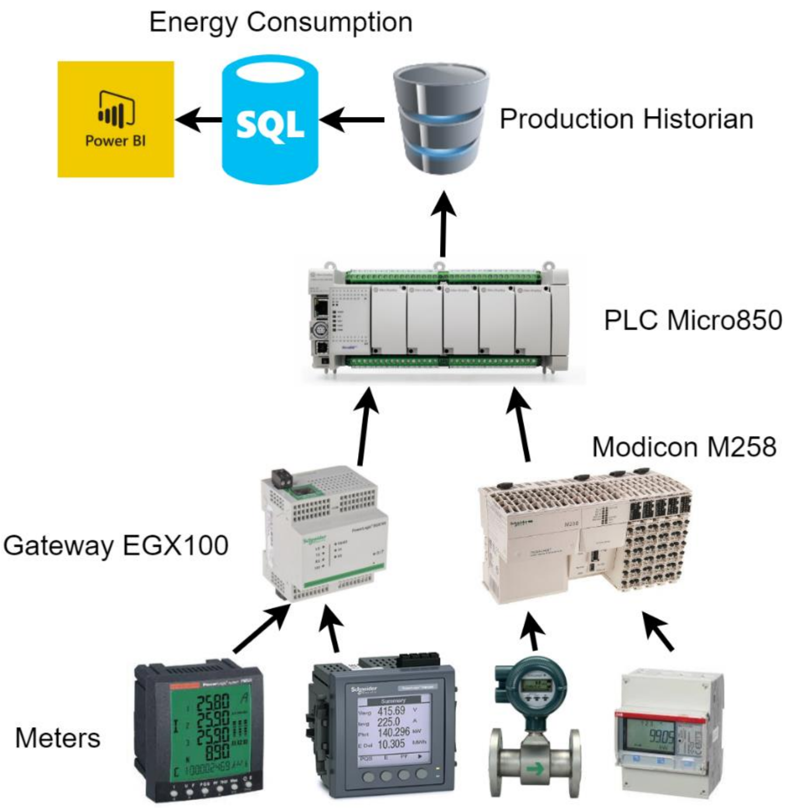

Figure 35: Energy Monitoring Data Flow Architecture

8.3.3. ITOT Architecture

Every IT solution in a corporate world must be secure in terms of cyber security and data leakage. Therefore, the data transfer within a system must be secure and encrypted. All users must be logged in with their Microsoft account and verified using PingID service.

There are multiple access levels.

1) Users can only read reports
2) Developers can read, edit and share reports with others
3) Administrators can set up workspaces, gateways, manage access, read, edit and share reports.

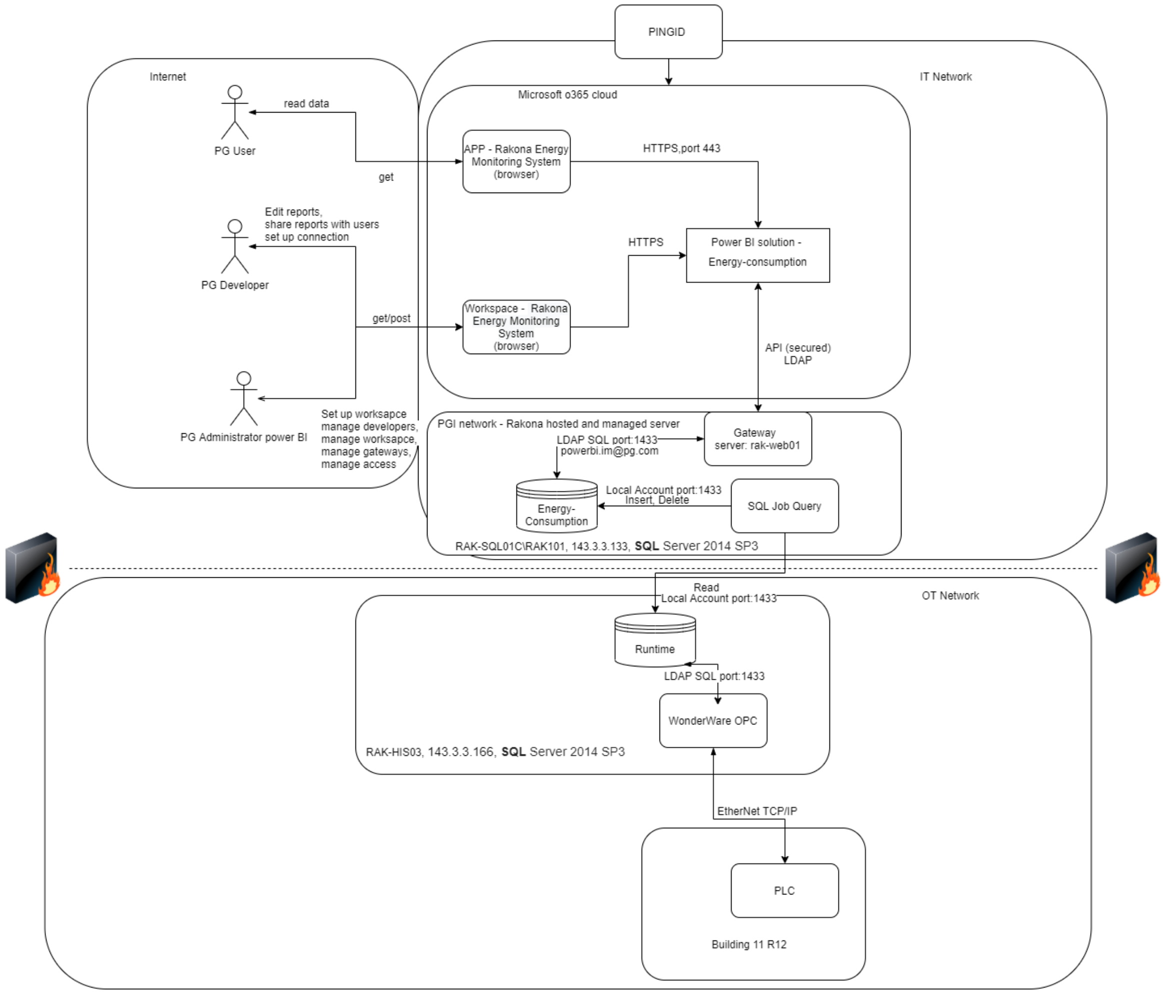

Figure 36: ITOT Technology Diagram

In the OT network data flows from PLCs to production Historian database. Then the data is transformed, linked and transferred to SQL database using automated SQL Query Job. Then the data gets pushed twice a day to Power BI dataset in Microsoft Office365 cloud storage through a gateway using secured API. Once the data is in the Power BI, it is ready for the user to be visualized in any web browser.

9. Energy Consumption Database

The data is stored in a relational database management system, which can be accessed using structured query language (SQL).

9.1. Data tables

The database contains 5 tables, which could be logically split into 2 types:

1) Master data tables (Master Data, Units and Limits)

The data into master data tables is entered manually. These tables are responsible for logical connection between all tables to enable filtering and to establish the structure of the factory.

2) Data storage tables (Actual Consumption and Total Consumption)

Data storage tables are filled and deleted automatically using SQL Query Job.

9.1.1. Master Data table

Master Data table is the heart of the database. It stores data about each meter tag and connects them with various attributes.

TagName: Specifies tag name in Historian.

EnergyType: Specifies energy type, which is measured by the meter. If there is NULL, it means that it is a tag specifying the amount of produced product.

Operation: Specifies a business unit within a factory.

Department: Specifies department, which is a subset of a business unit.

Line: Individual line within a department. It is an equivalent of process unit.

Equipment: Specifies a single or a group of machines.

SubEquipment: Type of an equipment (Fan, compressor, agitator etc.).

EquipmentGroup: Type of an actuator (Motor, compressor, etc.).

Comment: Possibility to add any comment needed. In some cases, it might be location, in others just the meaning of the tag described in words.

Date_inserted: Date and time of insertion of the tag into the database.

Totalizer: Specifies if the tag is a totalizer type or not.

	TagName	EnergyType	Operation	Department	Line	Equipment	SubEquipment	EquipmentGroup	Comment	date_inserted	Totalizer
1	BF_buggy_total_kg_actual	NULL	Dry Laundry	MSG	Admix	NULL	NULL	NULL	Total produced Final Product	2019-11-07 14:27:20.527	0
2	BlownPowder totalizer	NULL	Dry Laundry	MSG	TWR&Pumping	NULL	NULL	NULL	Blown powder totalizer	2020-01-13 13:49:35.653	0
3	DryScrap_Snek_Active_Power	Electricity	Dry Laundry	MSG	CRU	DryScrap Snek	NULL	NULL	NULL	2020-01-20 10:50:10.993	0
4	DryScrap_Snek_Totalizer	Electricity	Dry Laundry	MSG	CRU	DryScrap Snek	NULL	NULL	NULL	2020-01-20 10:50:25.140	1
5	E1_Active_Power	Electricity	Dry Laundry	MSG	TWR&Pumping	Exhaust fan	Fans	Motor	NULL	2019-10-31 12:31:26.483	0
6	E1_Energy_Totalizer	Electricity	Dry Laundry	MSG	TWR&Pumping	Exhaust fan	Fans	Motor	NULL	2019-10-31 12:32:54.483	1
7	E113_Active_Power	Electricity	NULL	TSD	AC	AC5	NULL	NULL	NULL	2019-11-25 10:25:24.653	0
8	E113_Energy_Totalizer	Electricity	NULL	TSD	AC	AC5	NULL	NULL	NULL	2019-11-25 10:35:34.020	1
9	E136_Active_Power	Electricity	Dry Laundry	MSG	Tankfarm	Raw Material Liquids	NULL	NULL	Tankfarm 171RM1, E136 - E14 - E12 - E138	2020-01-17 13:21:48.137	0
10	E136_Energy_Totalizer	Electricity	Dry Laundry	MSG	Tankfarm	Raw Material Liquids	NULL	NULL	Tankfarm 171RM1, E136 - E14 - E12 - E138	2020-01-17 10:29:44.480	1
11	E138_Active_Power	Electricity	Dry Laundry	MSG	Tankfarm	Lighting	NULL	NULL	Tankfarm 171RM1	2020-01-17 13:22:19.913	0
12	E138_Energy_Totalizer	Electricity	Dry Laundry	MSG	Tankfarm	Lighting	NULL	NULL	Tankfarm 171RM1	2020-01-17 10:30:27.470	1
13	E14_Active_Power	Electricity	NULL	TSD	Contractors	NULL	NULL	NULL	NULL	2019-11-25 10:21:11.423	0
14	E14_Energy_Totalizer	Electricity	NULL	TSD	Contractors	NULL	NULL	NULL	NULL	2019-11-25 10:39:48.927	1
15	E140_Active_Power	Electricity	Packing	PSG	Linka I	NULL	NULL	NULL	NULL	2020-01-20 10:52:51.303	0
16	E140_Energy_Totalizer	Electricity	Packing	PSG	Linka I	NULL	NULL	NULL	NULL	2020-01-20 10:52:57.023	1

Figure 37: Master Data table

9.1.2. Total Consumption

Total Consumption table stores totalized data of production runs. The data is sampled at the end of each run and difference between beginning and end of the run is calculated within SQL query.

TagName: Specifies tag name in Historian.

CollectionDate: Date and time of energy consumption collection based on the end of production batch.

Value: Total value of energy spending per specified production batch.

BatchID: Unique string value for each production run.

TagName	CollectionDate	Value	BatchID
E88_Energy_Totalizer	2020-07-02 07:25:04.613	1338	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E89_Energy_Totalizer	2020-07-02 07:25:04.613	232	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E86_Energy_Totalizer	2020-07-02 07:25:04.613	670	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E87_Energy_Totalizer	2020-07-02 07:25:04.613	861	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E85_Energy_Totalizer	2020-07-02 07:25:04.613	551	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E83_Energy_Totalizer	2020-07-02 07:25:04.613	805	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E82_Energy_Totalizer	2020-07-02 07:25:04.613	78	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E81_Energy_Totalizer	2020-07-02 07:25:04.613	418	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E79_Energy_Totalizer	2020-07-02 07:25:04.613	478	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E80_Energy_Totalizer	2020-07-02 07:25:04.613	171	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E78_Energy_Totalizer	2020-07-02 07:25:04.613	50	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E73_Energy_Totalizer	2020-07-02 07:25:04.613	0	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E72_Energy_Totalizer	2020-07-02 07:25:04.613	373	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E71_Energy_Totalizer	2020-07-02 07:25:04.613	30	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E70_Energy_Totalizer	2020-07-02 07:25:04.613	438	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E66_Energy_Totalizer	2020-07-02 07:25:04.613	218	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E143_Energy_Totalizer	2020-07-02 07:25:04.613	54	2018405_Y_DPLUS_ORION_Flash_91930850.0001
E65_Energy_Totalizer	2020-07-02 07:25:04.613	185	2018405_Y_DPLUS_ORION_Flash_91930850.0001

Figure 38: Total Consumption table

The form of BatchID value is in YYDDDNN_Product form, where YY indicates production year, DDD is the number of the production day in a year, NN is production number in given day and Product is simply name of the product. It is necessary, that when the solution is reapplied to other production lines, the same BatchID form is used.

9.1.3. Actual Consumption

The data from Actual Consumption table is used to draw a trend of energy spending throughout specified production run. Therefore, data is sampled every minute.

TagName: Specifies tag name in Historian.

CollectionDate: Date and time of energy consumption collection based on the end of production batch.

Value: Actual consumption spending value (in terms of electricity it is power).

BatchID: Specifies department, which is a subset of a business unit.

Status: Defines status of production line (1 means it is ON and 0 means OFF)

TagName	CollectionDate	Value	BatchID	Status
E86_Active_Power	2020-07-06 05:50:01.367	266	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E65_Active_Power	2020-07-06 05:50:01.367	24	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E71_Active_Power	2020-07-06 05:50:01.367	0.43798291683197	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E72_Active_Power	2020-07-06 05:50:01.367	0.813108325004578	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E138_Active_Power	2020-07-06 05:50:01.367	8.71465301513672	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E1_Active_Power	2020-07-06 05:50:01.367	36	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E136_Active_Power	2020-07-06 05:50:01.367	57.3229026794434	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E140_Active_Power	2020-07-06 05:50:01.367	9	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E81_Active_Power	2020-07-06 05:50:01.367	8	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E141_Active_Power	2020-07-06 05:50:01.367	0	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E85_Active_Power	2020-07-06 05:50:01.367	105	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E66_Active_Power	2020-07-06 05:50:01.367	0.790692448616028	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E14_Active_Power	2020-07-06 05:50:01.367	8.05290983407758E-05	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E83_Active_Power	2020-07-06 05:50:01.367	234	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E142_Active_Power	2020-07-06 05:50:01.367	5	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E143_Active_Power	2020-07-06 05:50:01.367	0	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
MSG_TWR_Gas_...	2020-07-06 05:50:01.367	525697.875	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0
E70_Active_Power	2020-07-06 05:50:01.367	1.16785717010498	2018509_Y_DPLUS_ORION_Flash_91930850.0001	0

Figure 39: Actual Consumption table

9.1.4. Units

Units table is used to differ energy type reports design in terms of colour and axes description.

PK: Primary key.

Energy_type: One out of five energy type.

Actual: Unit of actual consumption metrics.

Totalizer: Unit of energy totalizer value.

Color: Specifies the colour design of report page.

	PK	Energy_type	Actual	Totalizer	Color
1	1	Electricity	kW	kWh	#003DA7
2	2	Gas	m3/h	m3	#DAB300
3	3	Steam	m3/h	m3	#596157
4	4	Water	m3/h	m3	#86BBD8
5	5	Compressed Air	m3/h	m3	#5B8C5A

Figure 40: Units table

9.1.5. Limits

Limits table shall be edited by process technicians, who should be well educated about the process and to be able to estimate the limits, that must be set.

PK: Primary key.

BatchID: Product name that the limit is defined for.

LimitHigh: Defines a limit value for evaluation of a run as a ratio between energy unit and production unit (e.g. kWh per number of produced products).

Equipment: Equipment name that the limit is defined for.

PK	BatchID	LimitHigh	Equipment
1	Y_DPLUS_ORION_Flash	7.90000	Exhaust fan
2	Y_QPFIX_ORION_Flash	7.90000	Exhaust fan
3	Y_QUARTZ_ORION_Flash	7.90000	Exhaust fan
4	Y_DPLUS_ORION_Flash	2.15000	Airlift fan
5	Y_QPFIX_ORION_Flash	2.15000	Airlift fan
6	Y_QPFIX_ORION_Flash	2.15000	HPP
7	Y_DPLUS_ORION_Flash	2.15000	HPP
8	Y_QUARTZ_ORION_Flash	2.15000	Airlift fan
9	Y_QUARTZ_ORION_Flash	2.15000	HPP
10	Y_QPFIX_ORION (0)	2.15000	Airlift fan
11	Y_DPFIX_ORION_Flash	7.90000	Exhaust fan
12	Y_QPFIX_ORION_Flash	1.00000	Process fan

Figure 41: Limits table

9.2. Data retention

As already stated before, the database grows quickly with every single tag. In the testing phase 29 tags was used and 1-minute sampling period was set up. After 2 months the actual consumption table grew to 610 MB and the total consumption table grew to 1 MB. The system is meant to be used across the whole factory with many departments, so it is expected, that data from hundreds of energy meters would be entered into the database.

The monitoring system is designed in a way, that process technicians should use the actual consumption data on daily basis, therefore it is not important to store the data for years nor months. Actual consumption data is being deleted 2 months after collection. On the other hand, total consumption data is important to store for longer periods, because declining energy consumption trend shall be seen in bigger time frames. Total consumption data is set up to be deleted 2 years after collection.

10.Power BI solution

Once all data was in place, the reporting platform had to be chosen. One option was ThingWorx, which is an IoT industrial platform for data analytics and control. However, keeping in mind, that the monitoring system is developed for international corporate company, Power BI was a better option as it is developed by Microsoft and already standardized within the company.

Power BI is a cloud-based web application used for interactive data visualization. Published dashboards are accessible with Microsoft accounts from anywhere in the world. It supports basically any data source such as Excel sheets, Access database, SQL database, SAP, Azure, JSON and many others.

10.1. Power BI Dataset

Energy consumption database has been connected to Power BI and all the ~~connections~~relationships between tables have been created. Some additional tables have been created to transform some values and extract data from tags. For example, in Batch table there is product extracted from BatchID values. This transformation is later used to set limits for each production.

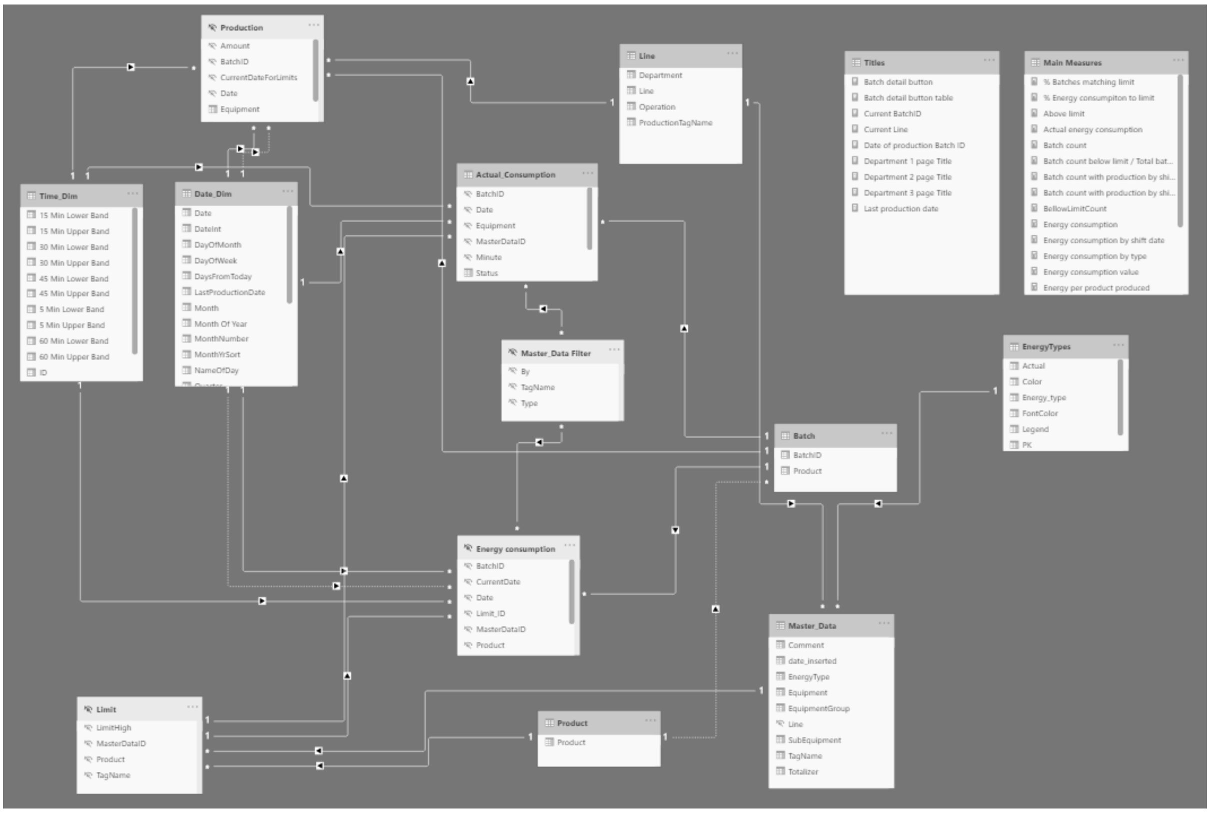

Figure 42: Power BI Dataset

10.2. Power BI reports

10.2.1. Compliance report

Compliance report is the most important report for process technician, as it is the one, which should quickly indicate, if they should pay attention to potential energy leaks from previous day or not. The days are set to be from 6 AM previous day to 6 AM current day. It consists of line and date filters and two tables. Process technician should open compliance report every morning before team meeting.

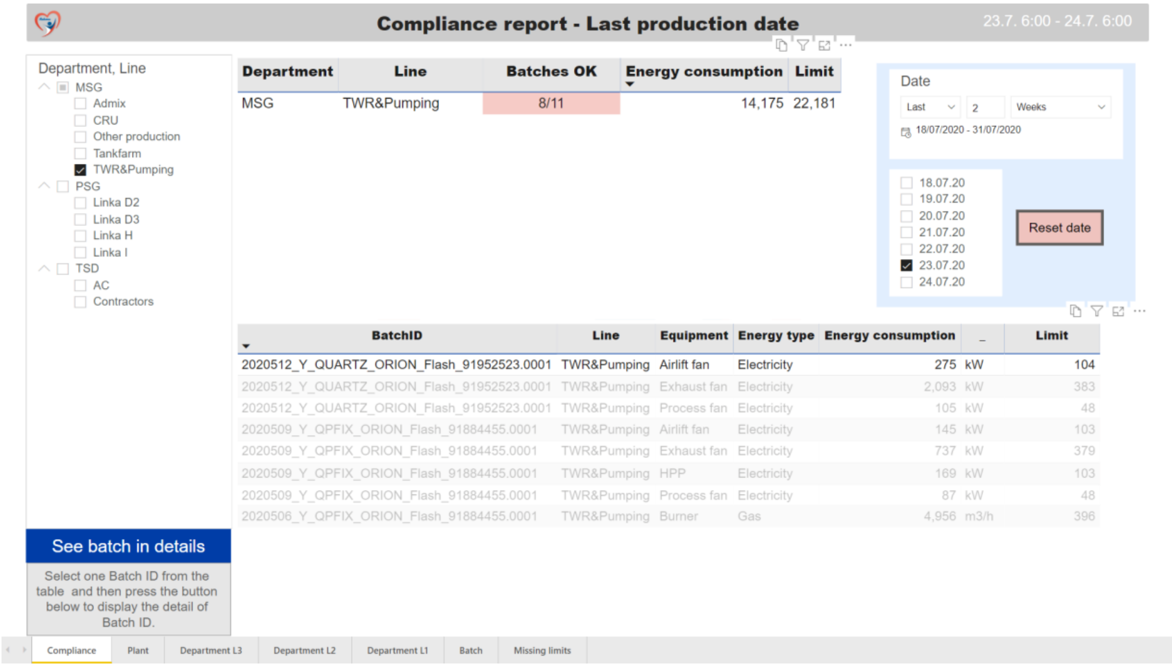

Figure 43: Compliance report

In the picture above can be seen, that 3 batches out of 11 were had higher energy consumption than it was planned. By selecting one row in the lower table "See batch in detail" button is activated and ready to redirect a user to batch report with appropriate filters.

10.2.2. Batch report

The technician can see the actual consumption trend throughout one particular run. They can observe the consumption based on status of the line and see the dependencies between each device. There are 3 ways how to enter Batch report. One can be either redirected from Compliance report or Department level 1 report with appropriate filters on or by selecting “Batch” at the bottom pane of the page. If the report is entered from the pane, there is additional filter for all batches, that are in the actual consumption data table.

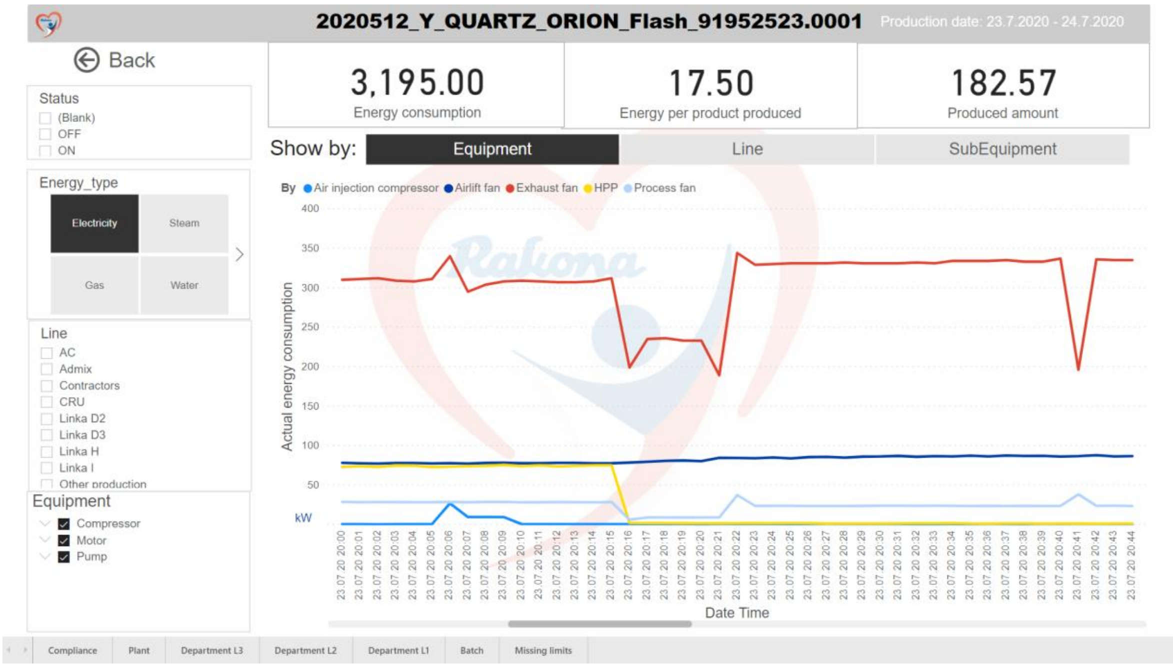

Figure 44: Batch report redirected from compliance report

Batch report should be the one, where the biggest savings will be found. Equipment groups can be filtered to make it easier to see dependencies between equipment with the same characteristics.

10.2.3. Department Level 1 report

Department Level 1 report gives a weekly overview to the process technician on energy spending. In "Total energy consumption" chart on top of the page the spending of each day with the limit is displayed. On the right in "Energy consumption per Batch" there is the overview of the batches produced in the selected time frame and line ordered by total energy consumption. If one batch is selected as in the picture below, the middle "Energy consumption per equipment" is filtered based on the batch and shows the totalizer energy value per each equipment with respect to the limit.

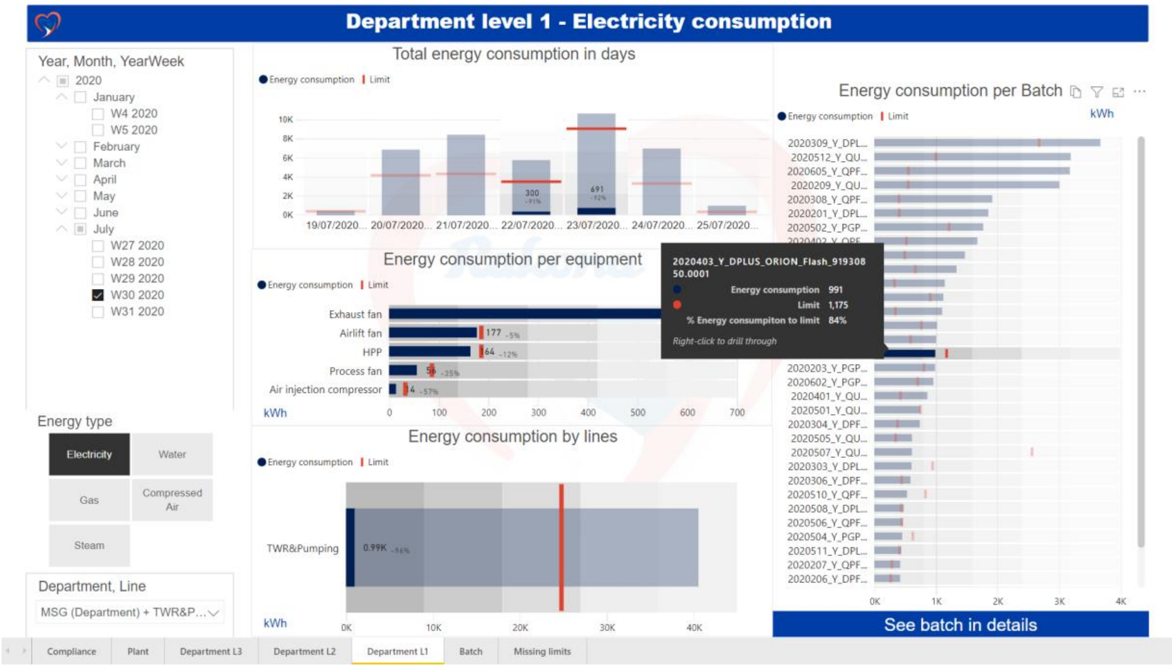

Figure 45: Department Level 1 report

In "Energy consumption by lines" one can see the totalizer energy values of all selected lines with the limit.

10.2.4. Department Level 2 report

Not only process technicians shall be interested in energy consumption, but also operating department managers. They are the ones, who are responsible for the whole department results. Every department has multiple production lines, therefore operating department managers cannot go into every little detail of energy spending, but they need to inspect energy spending trends.

Department Level 2 report gives weekly overview of energy spending of one department. One can filter by one or multiple production lines.

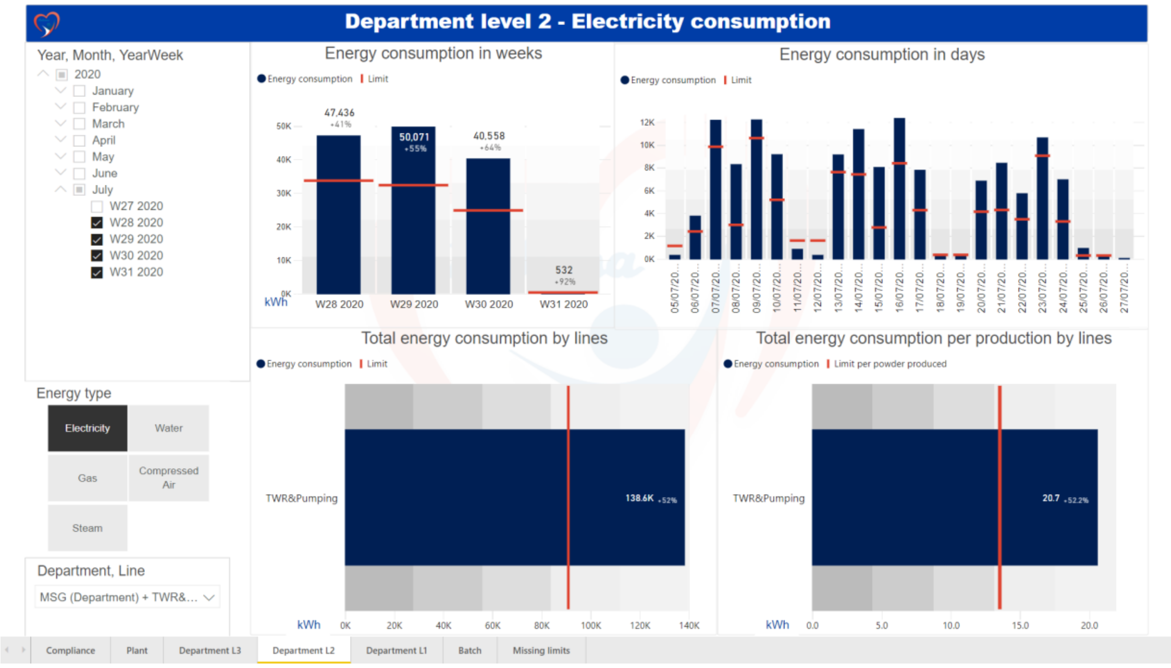

Figure 46: Department Level 2 report

10.2.5. Department Level 3 report

Department Level 3 report is similar as Department Level 2 with larger time scale. Weeks are converted into months and days into weeks. The purpose is to give monthly overview to operating department managers.

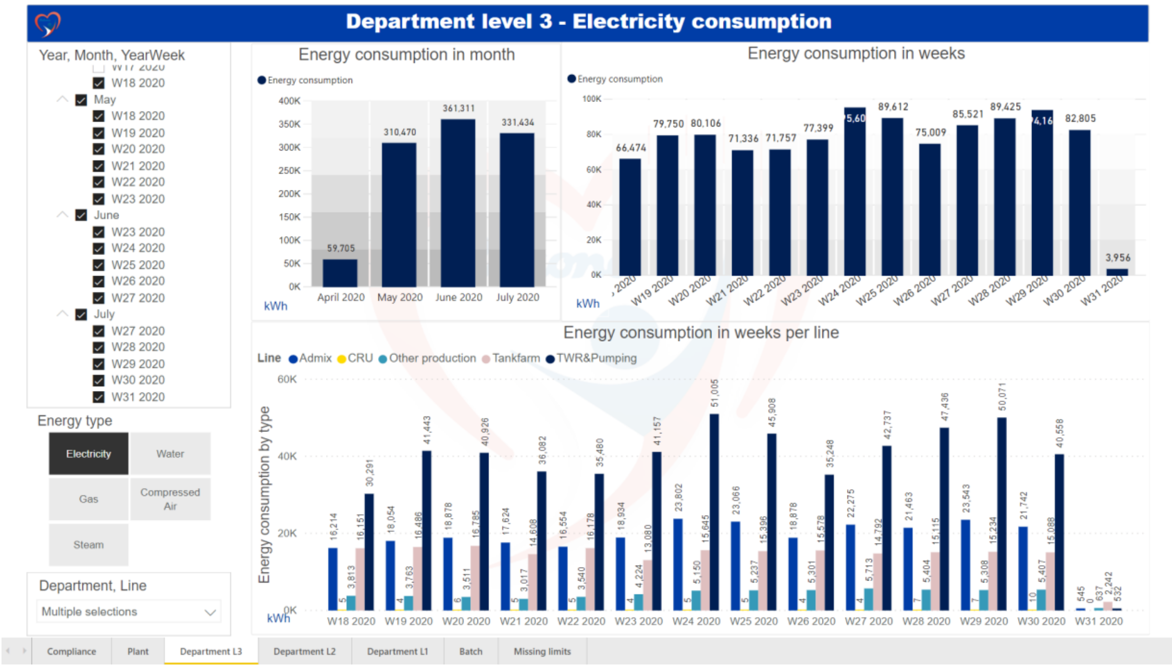

Figure 47: Department Level 3 report

10.2.6. Plant Level Report

Plant level report gives insights to factory director and operation directors of energy spending of each department. It is a report with the least amount of detail, which should give the most general data available. The report should be used for product pricing and tracking energy spending on the broadest possible level.

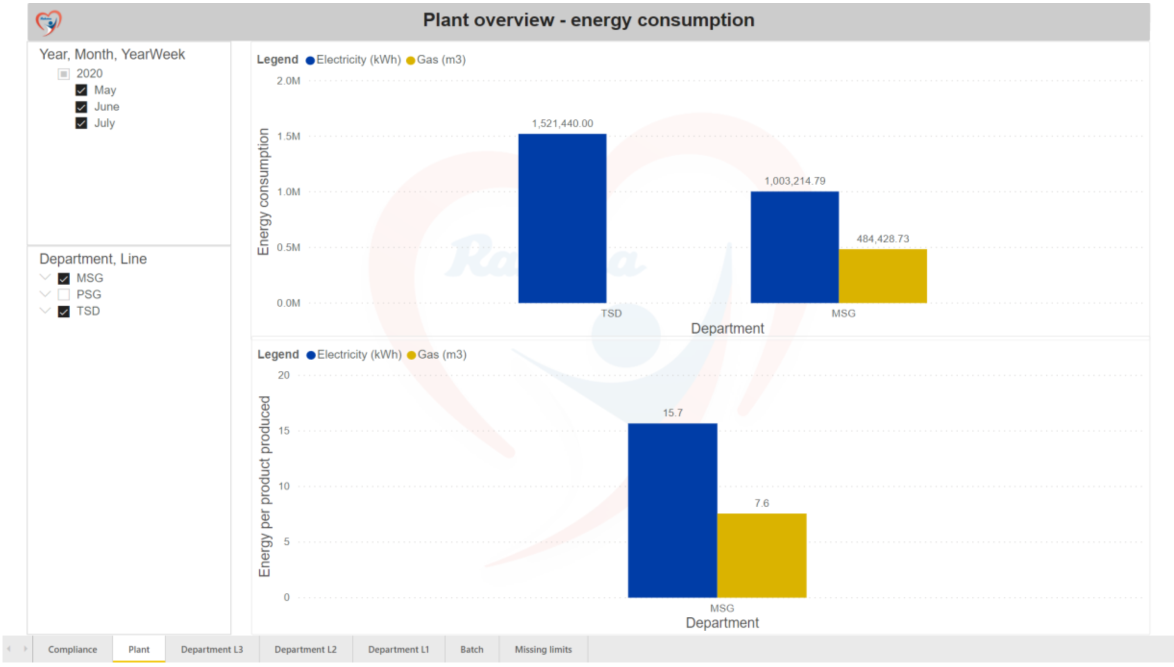

Figure 48: Plant Level report

11.Summary and outlook

The creation process of energy monitoring system is described in this master thesis. It starts with the theoretical background of existing solutions and energy metering possibilities and continues with system design, energy meters mapping, data architecture setting and SQL database design and ends with automated reporting system in Power BI.

The designed system extends the ownership of energy consumption to process technicians. As the factory is near to city centre, it needs to be a good neighbour to all citizens and be environmentally friendly not only from emissions perspective, but also energy spending perspective, because it uses the same power grid as inhabitants.

I utilized my theoretical background, that I acquired through my study program, when I was designing the data architecture. It helped me with mapping of the meters, when I was setting up all the communication between devices. I immediately knew what I had to do when I stumbled upon Modbus communication protocol. I am thankful for all the devices I could use to develop the system architecture.

I have learned many important lessons through this thesis. One of them is the need of communication with the future users of the system in the process of design. They gave me many important insights, that I would overlook. Other one was teamwork, as I was not granted a permission to build my own database on the corporate server. I had to design everything in hand on paper and in excel sheets to explain the desired relationships between tables, which made me realize some errors. Even though I could not create the database myself and set up the SQL query jobs, but I still had to write them and prove their functionality before they were implemented into the database.

It is expected that there are going to be many changes in the process control strategy in order to optimize the energy consumption. There are going to be new sequences, which are going to automatically turn all the devices off in order to achieve zero idle energy. Once the energy consumption is minimized, it will allow to the factory to use energy only from renewable energy sources.

There are still many ways how to improve the monitoring system and I will keep on working to improve it. One of them is to automate the limit setting. Currently, the system relies on the technician’s knowledge of the system to set the correct limit ratios. Another needed functionality is to be able to track energies in support departments, that have no measurable product. The idea is to set the limit ratio as energy consumption per specified time instead of produced product. But before any further development the system needs to be properly tested and expanded to other departments and cover all the lines within the factory.

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Table of Figures

APPENDIX A – SQL QUERY FOR TOWER DATA DOWNLOAD

```
/* Stahovani dat Total Power pro MSG Tower */

SELECT *
FROM OPENQUERY
(RAK_HIS03, ''
DECLARE @StartDate DateTime
DECLARE @EndDate DateTime
SET @StartDate = dateadd(d,-1,getdate())
SET @EndDate = getdate()
SET NOCOUNT OFF

select      tag as TagName
        , min(StartDateTime) as CollectionDate
        , cast(max(vValue) as float) -  cast(min(vValue) as float) as Value
        , BatchId
from
(

SELECT t1.tag
        , cast(t1.vValue as float) as vValue
        , t2.StartDateTime
        , t2.vValue as BatchId
from (

SELECT temp.TagName as tag, vValue,StartDateTime From (
SELECT  *
 FROM History
WHERE History.TagName IN
(''''DryScrap_Snek_Totalizer'''',''''E143_Energy_Totalizer'''',''''E142_Energy_Totalizer'''',''''E141_Energy_Totalizer'''',''''E140_Energy_Totalizer'''',''''E65_Energy_Totalizer'''',''''E82_Energy_Totalizer'''',''''E81_Energy_Totalizer'''',''''E80_Energy_Totalizer'''',''''E79_Energy_Totalizer'''',''''E78_Energy_Totalizer'''',''''E138_Energy_Totalizer'''',''''E136_Energy_Totalizer'''',''''E89_Energy_Totalizer'''',''''E88_Energy_Totalizer'''',''''E87_Energy_Totalizer'''',''''E86_Energy_Totalizer'''',''''E85_Energy_Totalizer'''',''''E83_Energy_Totalizer'''',''''E14_Energy_Totalizer'''',''''E113_Energy_Totalizer'''',''''E1_Energy_Totalizer'''',''''E66_Energy_Totalizer'''',''''E70_Energy_Totalizer'''',''''E71_Energy_Totalizer'''',''''E72_Energy_Totalizer'''',''''E73_Energy_Totalizer'''',''''MSG_TWR_Gas_Q.Val_CtrlTotal'''')
AND wwRetrievalMode = ''''Cyclic''''
AND wwResolution = 1000 * 60 * 5
```

```
 AND wwVersion = ''''Latest''''
AND DateTime >= @StartDate
AND DateTime <= @EndDate) temp
LEFT JOIN AnalogTag ON AnalogTag.TagName =temp.TagName
LEFT JOIN EngineeringUnit ON AnalogTag.EUKey = EngineeringUnit.EUKey
LEFT JOIN QualityMap ON QualityMap.QualityDetail = temp.QualityDetail
WHERE temp.StartDateTime >= @StartDate
) as t1
join
(
SELECT temp.TagName as tag2 , vValue,StartDateTime From (
SELECT  *
 FROM History
WHERE History.TagName IN (''''MSG_CRU_QW_Data.BatchID'''')
AND wwRetrievalMode = ''''Cyclic''''
AND wwResolution = 1000 * 60 * 5
 AND wwVersion = ''''Latest''''
AND DateTime >= @StartDate
AND DateTime <= @EndDate) temp
LEFT JOIN AnalogTag ON AnalogTag.TagName =temp.TagName
LEFT JOIN EngineeringUnit ON AnalogTag.EUKey = EngineeringUnit.EUKey
LEFT JOIN QualityMap ON QualityMap.QualityDetail = temp.QualityDetail
WHERE temp.StartDateTime >= @StartDate
) as t2 on t1.StartDateTime = t2.StartDateTime
)
AS subquery
group by BatchId,tag,convert(date,StartDateTime )
''
)'
```