Journal of Applied Technical and Educational Sciences
jATES
ISSN 2560-5429
http://jates.org

Supervision and Optimization the Application of Manufacturing Resources with the Support of IoT Devices and Technologies

Adrienn Koncz [1*], Attila Gludovátz [2]

[1*] *University of Sopron, Faculty of Wood Engineering and Creative Industries, Bajcsy Zsilinszky út 4, Sopron 9400, Hungary, koncz.adrienn@uni-sopron.hu*

[2] *Eötvös Loránd University, Faculty of Informatics, Károlyi Gáspár tér 4., Szombathely 9700, Hungary, gla@inf.elte.hu*

Abstract: *This study was conducted at a multinational furniture company, aligned with Industry 4.0 standards, where a cyber-physical system (CPS) was already implemented with its respective hardware and software components. The primary purpose of the CPS is to gather data on the consumption of production resources such as energy, water, and compressed air, and to oversee the operational processes within the company. Initially, data collection was solely focused on the energy utilization of the production machinery and the produced workpieces. However, over time, we have evolved the cyber-physical system to broaden the data collection spectrum. This expansion was imperative to encompass the energy and other related parameters of the production support equipment, alongside the water consumption metrics. The subsequent phase of the research delved into exploring avenues to foster energy-conscious work practices. With the activation of the analytical application, the financial ramifications of superfluous energy consumption could be ascertained, and the proficient functioning of the production machinery could be real-time monitored via computers stationed within the facilities. Consequently, this setup serves to motivate employees towards adopting more energy-efficient work habits.*

Keywords: *Industry 4.0; data analysis; energy management; production optimization.*

1. Introduction

Industrial revolutions have been taking place around the world for nearly 240 years. The first industrial revolution dates to the 1780s, when the first mechanised looms were established and the first factories with steam engines were opened. The second industrial revolution took place at the end of the 19th century, when electricity was used to power the machinery in the factory. A highlight from the second industrial revolution was the introduction of the conveyor belt in a slaughterhouse in Cincinnati (USA), which allowed the distribution of labour there. If we compare the technological features of the first and second industrial revolutions, we can see how much progress has been made in industrial companies over the last 100 years. The outbreak of the third industrial revolution also had to wait about 100 years. It is estimated to have started in 1969, when the first programmable logic controller was created, enabling automation in factories [1]. In addition, there was rapid development in IT and electronics in almost all manufacturing sectors. This rapid progress brought us to the threshold of a next industrial revolution in the 2000s [2]. The start of the fourth industrial revolution is still debated, but the term was first used in 2011 at the Hannover Expo. If we look at all four industrial revolutions together, we can see how much technological progress has been made in a short period of time in the industrial sector almost all over the world [3]. We have moved from steam-driven machines to computer or artificial intelligence-driven machines, from manually recorded production and other data to digitised data and data stored in the cloud. As for technological progress, it is important to note that over the years, human work has been replaced by robots in many areas. This is often seen as a negative factor, because it has led to the loss of many jobs, but in fact it is a huge help in production and speeds up production processes [4]. For example, if we look at the automotive industry, one or more robots can move heavy car parts from point A to point B, assemble them, and perform other tasks in much less time than humans. Of course, there are other advantages to the presence of robots in the fourth industrial revolution, as it is still happening in time. This includes, for example, the use of cloud services, advances in IT and network security, continuous data measurement, whether it is about any environmental factor such as temperature, humidity, or even industry-related processes such as production piece count, power consumption, condition monitoring [5]. Nowadays, we can really measure everything in the production of a product and back it up with numbers. So, if we look at the example of a piece of furniture, we can say how much electricity and other resources (water, compressed air, heat) were used in the production of a perfectly normal wooden dining chair. From these numbers, it is also possible to determine the exact cost of raw materials and resources directly and indirectly included in the value of a product. Previously, indirect costs could only be determined according to some dividing method or by estimation based on experience, but now we are able to calculate the amount of increasingly accurate indirect costs with calculations based on data [6].

During our research and work, we used the opportunities provided by the fourth industrial revolution, or more popularly known as "Industry 4.0", to apply new methods at a furniture industry company that is already moving in the direction of this kind of development [7].

Our main goal is to measure consumptions of the furniture manufacturing company’s resources and detect operations and devices which are working wasteful. A cyber-physical system has been built for reaching that aim. In the beginning (2016/17), we collected data about the electricity consumptions (useful and useless). Later, the system and its database have been extended to measure and collect data about other resources' consumption (water, indirect electricity use etc.). These parts of the system are introduced in this section besides the technical references and scientific citations.

In the second section, we demonstrate our data collecting, analysing, and reporting techniques related to the manufacturing and its supporting processes. Dashboards, indicators, and methods are defined to monitor and control the consumptions of resources.

In the third section, we demonstrate our results. By the company's water consumption, we have identified a part (fire service practice), where a problem has raised that we solved with the help of cyber-physical system. After that, a useless compressor was identified by our data collecting and representing system. Furthermore, by the efficiency of compressors, we define a key performance indicator that should be taken above a limit. The extractor and its exhaust fans support the machines, so they connect to the manufacturing in an indirect way. Their indirect consumptions (and working costs) are directly connected to machines by our calculation method. The next phase of the research was the examination of the use of cloud services in an industrial environment and the possibilities of encouraging energy conscious work. We found a solution to move parts of the cyber-physical system to the cloud. With the analytical application operating in the cloud, the costs of useless energy consumption can be calculated, and the efficient operation of the production machines can be monitored in real time on the computers in the plants. This way, the employees are encouraged to work more energy consciously.

Finally, we summarise our work, results, and paper.

1.1. The initial steps of the research and the configuration of the cyber-physical system

In the 2016/17 financial year (from September to August), there was an opportunity to collaborate with a multinational furniture industry company, where the main goal was to modernize the company's IT system, including the hardware and software environment, according to the current industrial innovation trends. For this purpose, a cyber-physical model system was built, which is the basis for the company to operate according to the criteria of Industry 4.0 [8]. For this reason, a framework for monitoring and managing energy consumption was developed, which allows the comparison of energy consumption data with actual production data. This enables operational decision-makers to monitor and manage the performance of production machines and their associated systems, and thus make more effective strategic decisions. The physical aspects of the initial cyber-physical system include electricity metering sensors, network cables and switches, server hardware. In terms of the software part of the system, it includes: a Supervisory Building Control and Data Acquisition system (SCADA), an enterprise management system, a database management system, a business intelligence system [9][10].

This is where the cyber-physical system was designed and built. The concepts, architecture, and data flow directions of the system can be seen in Figure 1.

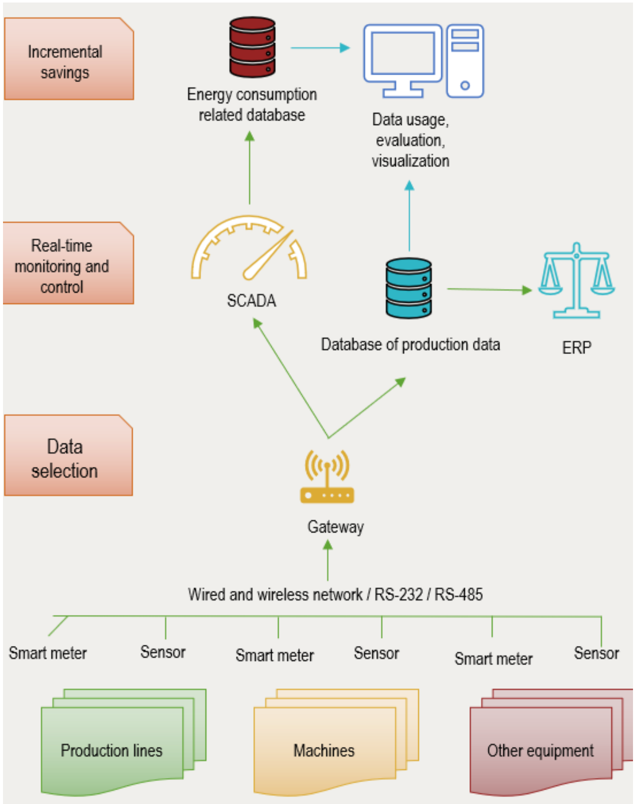

Figure 1. Structure of the cyber-physical system in 2017

It can be seen in the previous figure that sensors have been installed for production machines and other production support devices, which are equipped with MODBUS TCP/IP or Remote Terminal Unit (RTU) interfaces, particularly suitable for central data acquisition in industrial systems. Sensors record key electrical parameters such as currents, voltages, power factors, parameters describing power and energy values and more. The sensors transmit data to the SCADA system and the Enterprise Resource Planning (ERP) system via the company's internal network. We then connect the production and energy consumption data using business intelligence software, which also generates various reports and statements. These illustrate trends and the close correlations between data sets.

In the 2017/18 financial year, the system was physically expanded in addition to increasing availability and reliability. In the previous sample system, about 10 machines and equipment were installed and measured, but this year the number of measured and tested equipment rose to over 100. For this, not only the sensors were needed, but also the networks at the company had to be expanded. From a software point of view, new reports were generated to track both useful (produced) and useless (operated but not produced) energy consumption of the machines in 10-minute intervals (Figure 2) [11].

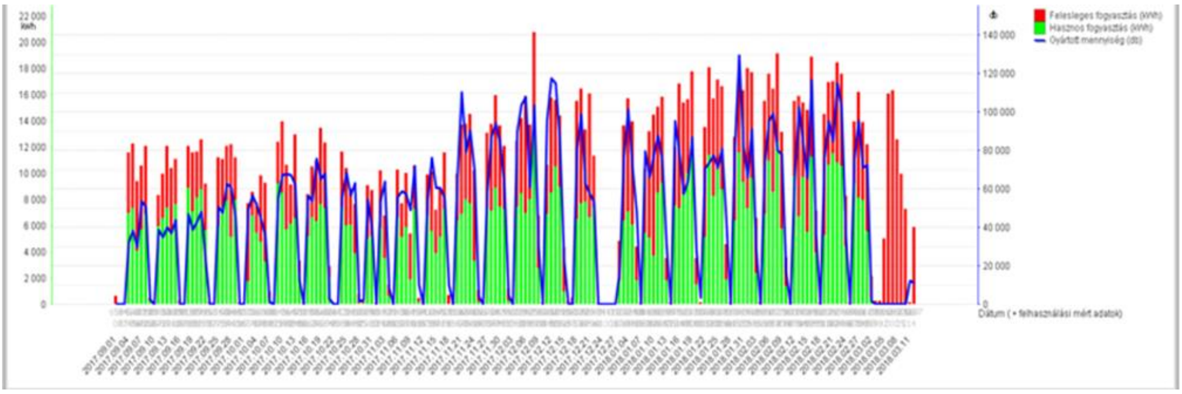

Figure 2. Measured consumption and production data for the 2017-2018 financial year (September 2017 to March 2018) in the framework (blue line: number of pieces produced, green part of column: useful electricity consumption, red part of column: useless electricity consumption; useful: production occurred, useless: no production occurred)

By monitoring the electricity consumption, the increasingly wasteful operation of a piece of equipment was revealed (Figure 3), so that preventive maintenance (or replacement) could be carried out as an operational measure.

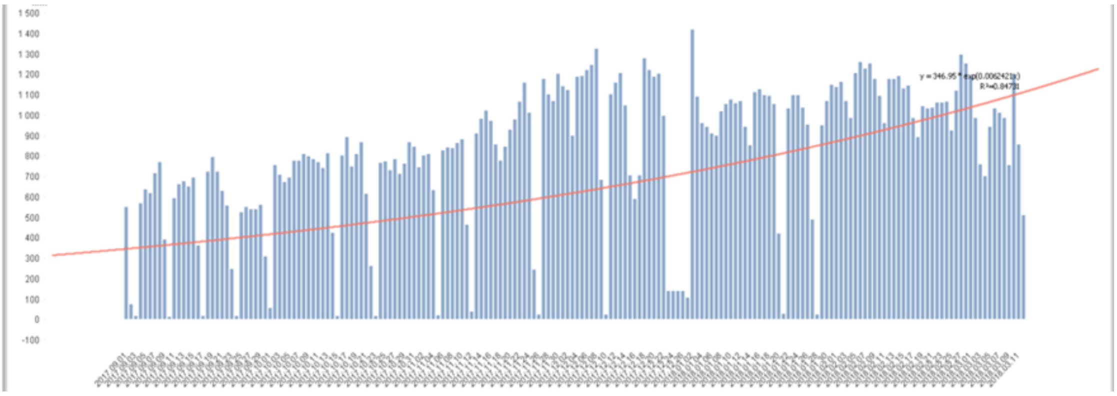

Figure 3. Daily energy consumption and trend line for a given equipment from September 2017 to March 2018

At the end of this phase (2018), the efficiency values of a production machine were compared, in other words, how many pieces of product it could produce from one kWh of energy consumption (Figure 4).

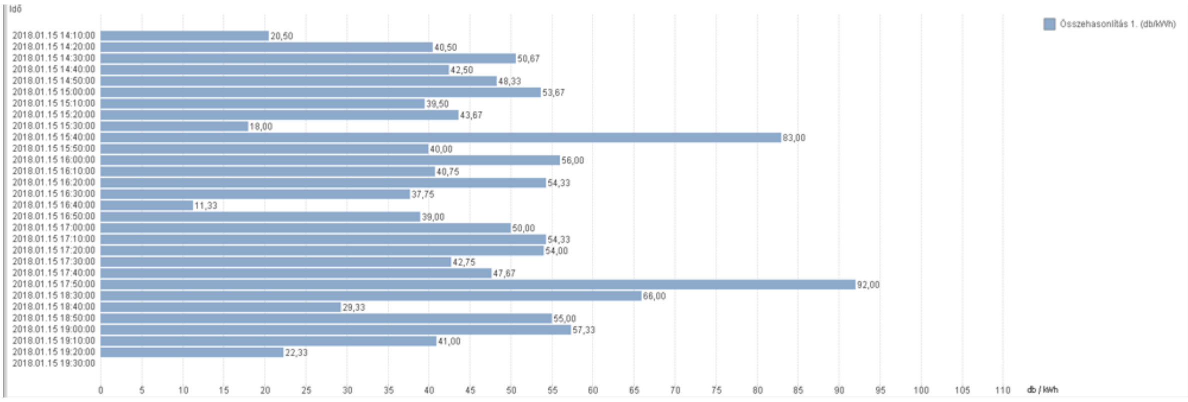

Figure 4. Production efficiency for a given product and machine: how many workpieces were produced using 1 kWh of electricity

Background to the research: a cyber-physical system was developed to collect and analyse electricity consumption data throughout the factory. In addition, it was possible to compare the energy consumption data with the production data, so that trends showing the comparison between production and electricity consumption (pcs/kWh, kWh/pcs, m^2/kWh) can be viewed for a given period or filtered for a given production machine. In the beginning, only number of pieces was recorded, but now the system has been refined to the extent that the number of pieces is not sufficient or does not always tell us much, because it does not matter whether the machine is working on a small board or a few square metres of work. It is easy to see that this does not mean the same amount of work, so a refinement was necessary [11].

1.2. Development of the cyber-physical system and transformation of the database

After defining the future goals of my research, the first task was to design and implement, step by step, the hardware and software improvements to the existing cyber-physical system. The development of the cyber-physical system was necessary because we no longer wanted to measure only the electricity consumption of the production machines, but also to connect all other production support equipment (exhaust fans and compressors) to the network and measure their energy consumption and other data. To do this, we also needed to install sensors to measure consumption and/or production parameters [12]. The company's specialists willingly assisted in the acquisition and installation of the sensors, so this phase was completed relatively quickly. After the necessary configurations, it was already possible to measure the electricity consumption data of the exhaust fans and compressors. For these machines, it was important to measure several parameters, so we also started to measure the air cubic metre extraction and emission volumes, also using sensors. Our main goal was to use the data input, just as we did for the production machines, to make different analyses and, together with the company management, we wanted to know more about the resource use of the factory's operations.

The question may arise why we started looking at the performance of compressors and exhaust fans, when the main role in production is played by production and working machines and products. The reason is simple: all the other equipment alongside the production machines proved to be quite large consumers of electricity, but the company could only have guessed this, there was no proof. When we had been collecting data for these machines for a year or two, we managed to produce an annual analysis which shows very clearly that exhaust fans are indeed the biggest energy consumers, but that the consumption of compressors is also significant. Figure 5 shows the company's total electricity consumption in 2020, which totalled more than 12 million kWh. The figure also shows that of these 12 million kWh, 3.8 million kWh were consumed by exhaust fans and more than 4 million by production machines. Compressors accounted for 1.3 million kWh, which is outstanding on an annual basis compared to other consumers. When we saw that exhaust fans were consuming so much, we had new goals for the research. Initially, it was not possible to relate the electricity consumption data of exhaust fans to their production performance. For this reason, the main purpose was also to study the useful and useless energy consumption of extraction fans. In the case of exhaust fans, useful electricity consumption means that the exhaust fan was running while the machines were producing products; useless electricity consumption means that the machines were not producing any products while the exhaust fan was running. To convert indirect costs into direct costs, a few modifications and extensions to the cyber-physical system were necessary [13].

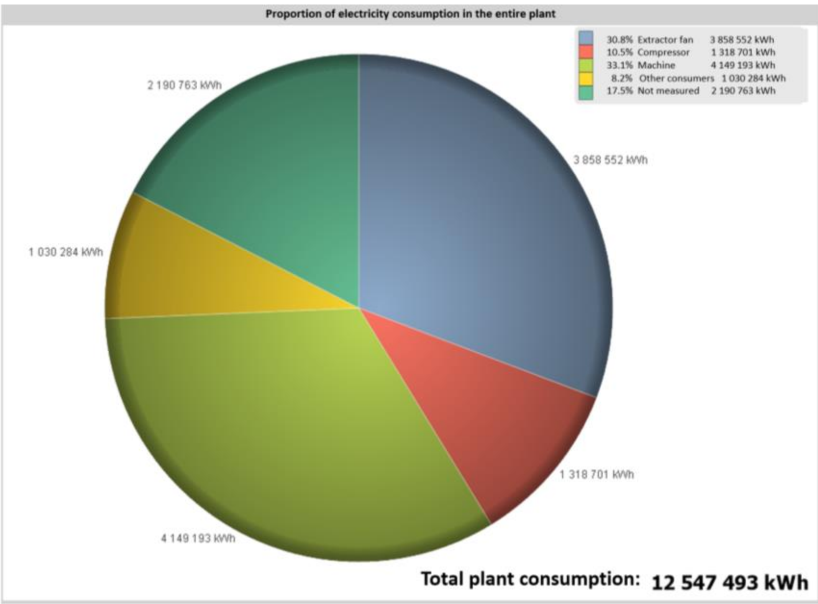

Figure 5. Electricity consumption in 2020

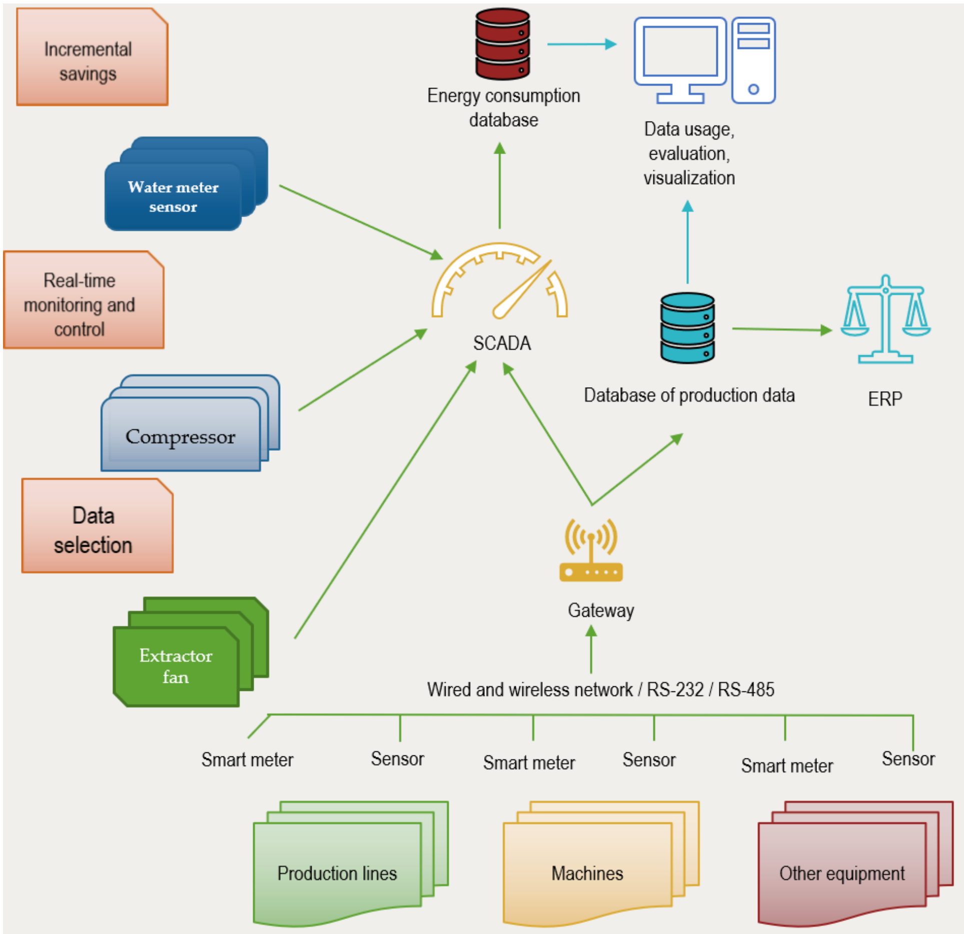

Figure 6. Construction of the extended cyber-physical system

Figure 6 illustrates the architecture of the extended cyber-physical system and the direction of data flow. Here it can be seen that new equipment has been added (compressors and extractors) and water consumption is also included as a measurement parameter, which can be monitored in the SCADA system [14]. Thus, the measured data of the consumption of additional resources (besides electricity) used in the production can be stored and monitored in the database of the SCADA system.

At the beginning of the research, a separate database had to be created at the company to store historical data (Figure 7), as the data structures in the internal database of the SCADA software were not suitable for efficient and fast work. In addition, the conversion was also intended to allow the energy consumption data to be linked to other systems (e.g., ERP) and to allow the storage of data on extractor fans, compressors, and water consumption in the database.

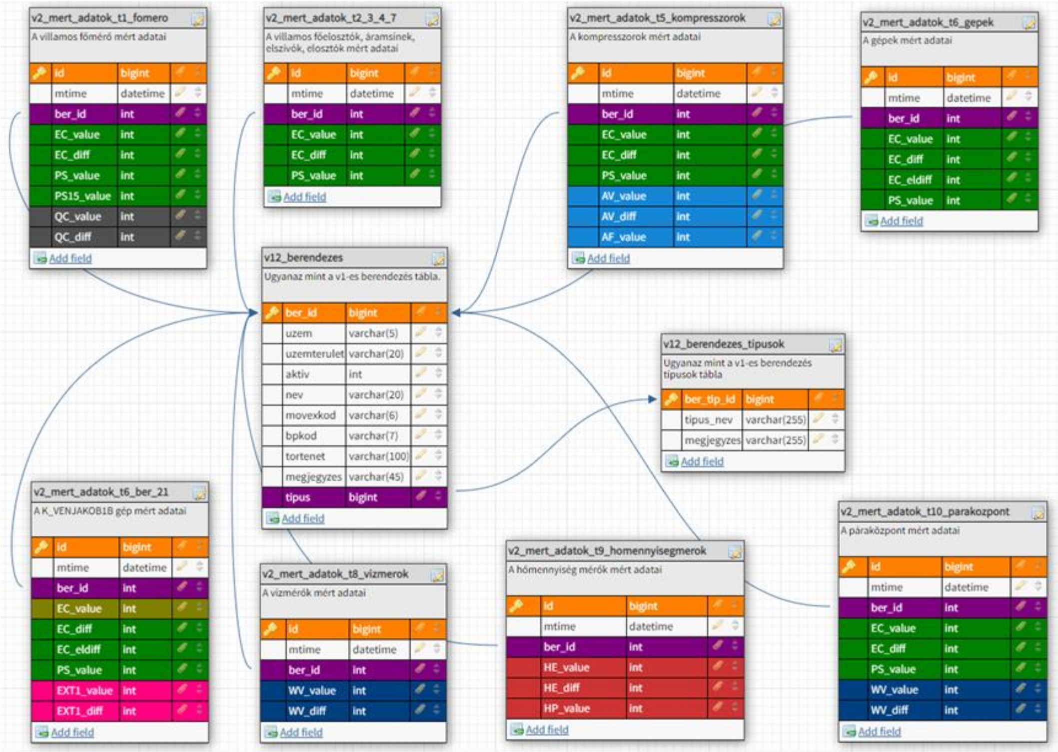

Figure 7. Database structure from 2021

2. Methods

In this section, the data collecting and analysing methods will be introduced to get scientific results.

2.1. Monitoring the company's water consumption

Water entering the company's territory supplies two plants and the office buildings. We classified the incoming water into three main groups, the first is the so-called social water, within which we distinguished between wastewater and so-called domestic water consumption

[15]. The other large group is the water used during production, which appears in the form of water vapor, which is also part of social water. The third group includes the fire service water usage, which in the best case only takes place when there are fire drills in the factory area.

The company uses almost the largest amount of water during production. Humidification during production is essential in furniture manufacturing, as the production of various furniture components requires a predetermined humidity and moisture content. The factory makes furniture elements from three types of wood: beech, birch, and oak. All three types of wood have the same required moisture level, so it is not necessary to change the amount or intensity of water vapour emission during the processing of each type of wood, but this can be done at a uniform rate and volume. On the other hand, it should be noted that different amounts of water vapor must be provided in different areas to achieve the minimum moisture content of the workpieces. For example, workpieces move relatively quickly in a production machine, while they are in the same place in the warehouse, thus, the humidification of the plant and storage areas must be ensured in a different way. For the data collection, it was not necessary to separate the amount of water vapour emissions in relation to the three tree species, but all emissions were collected and analysed together. The results related to water vapor emissions are presented in the following figures.

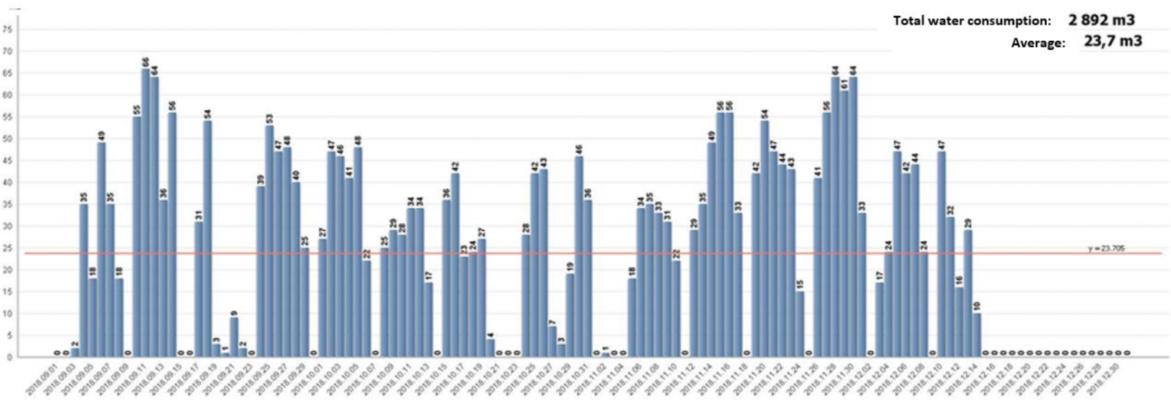

Figure 8. Water vapor emissions from September to December 2018

Figure 8 shows the amount of water vapor used in plants in a daily breakdown in the period from September 1 to December 31, 2018. It can be clearly seen from the columns of the diagram that the emission of water vapor occurs uniformly. Those with a value of zero are days that were weekends and holidays, so production was not running. This uniform use of water vapor can be observed until March 2020, when the shutdown caused by COVID-19 intervened. This period is shown in Figure 9.

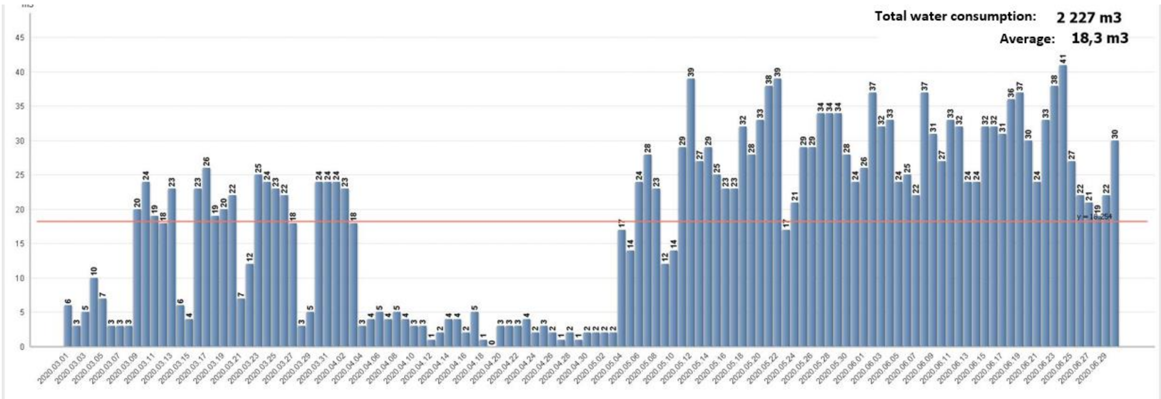

Figure 9. Water vapor emissions during the first COVID-19 period (March 1 to June 30, 2020)

In Hungary, online working was introduced from March 15, 2020. As the diagram shows, the actual COVID-19 shutdown at the company occurred in April, which lasted for a month in a very strict manner. After this period, production returned to normal, and even on weekends (Saturdays and Sundays), work was in full speed. It is also noticeable that water use on weekdays has increased compared to the months at the beginning of the year. From this, we conclude that the loss of work and production in April was continuously made up on weekends to be able to fulfil the orders.

2.2. Monitoring the energy consumption and other parameters of production support equipment

The next major topic of our research was the examination of the energy consumption and other parameters of the production support equipment, more precisely the compressors and exhaust fans operating in the plants. The use of compressors and extractors is essential because compressors provide the compressed air needed to operate some production machines. Exhaust fans are mainly responsible for keeping the environment of the machines clean and stable, because a large amount of dust and wood chips are generated during the processing of wooden furniture elements. This accumulated waste must be removed from the machining areas as efficiently as possible [16]. In the case of compressors, we also monitored the number of cubic meters of air produced and compared it with electricity consumption. In the case of exhaust fans, we managed to make major changes to the cyber-physical system. Thanks to our results, we are now able to monitor not only the electricity consumption and the area volume (m^2) of workpieces produced for a single production machine, but we can also partially charge the electricity consumption of the exhaust fans directly to the production machines. These measured parameters are presented in Figure 10.

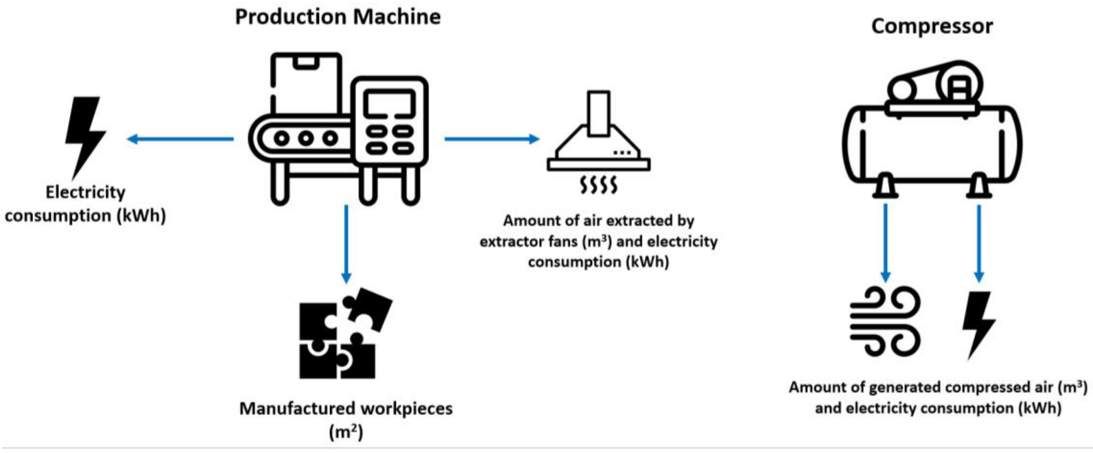

Figure 10. Measured parameters of a production machine and a compressor

2.2.1. The energy consumption and compressed air emissions of compressors

The compressor is the equipment responsible to produce compressed air. Compressed air is a secondary energy carrier, which is mainly used in industry for the mechanical operation of work machines, machine tools, and industrial robots [17]. The furniture company in our research also has several production machines that require compressed air to operate. At the beginning of the research, we had no information on the amount of compressed air emitted, and very limited information on the consumption of electricity, so together with the company's employees, we considered it important to examine the compressors operating in the plants.

In the company's plants, there are several compressors that are connected to one compressor housing (Figure 11). Before the start of our work, only the compressor housings were equipped with sensors, which measured the electricity consumption data of all compressors in aggregate. In order to ensure a successful and efficient outcome of the study, it was agreed that additional sensors should be installed at each compressor. The sensors installed on the compressors can measure how many cubic meters of compressed air they generate and how much electricity they consume, broken down into equipment.

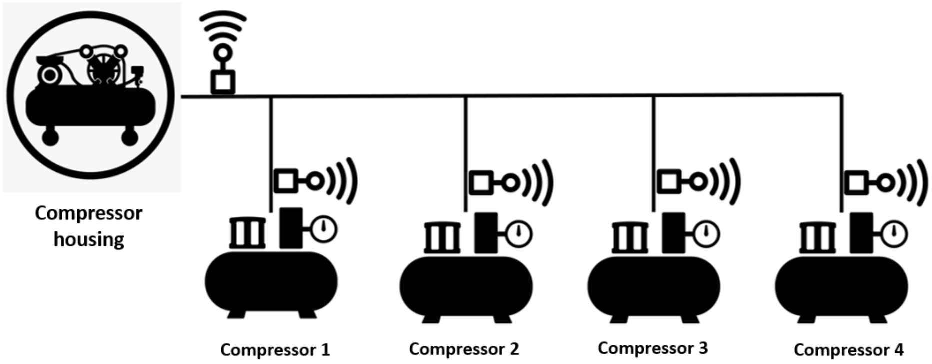

Figure 11. Construction of a compressor housing

Regarding the compressors in the plants, it is also important to know that each of the company's two plants has a large compressor house, to which a total of 8 compressors are connected, 5 in plant A and 3 in plant B. In the two plants, not all compressors are running at the same time, so for example only three of the eight compressors are running at any one time and two are in standby or off mode. This is a method of efficiency and energy management because there is a load balancing device that monitors the operation of the compressors to ensure that they are roughly balanced: that there is no possibility of a compressor being over- or under-utilised.

2.2.2. Exhaust fans energy consumption related calculation method

The other large group of equipment we examined, in addition to compressors, were the exhaust fans. Our main goal with the exhaust fans was to be able to charge their electricity consumption to the production machines they support. In order to achieve our goal, it was also necessary to install sensors in the beginning. New sensors were installed for the shutters, which measured the state of the shutters (open or closed). In addition to the condition monitoring sensors, consumption sensors were also installed to measure electricity consumption.

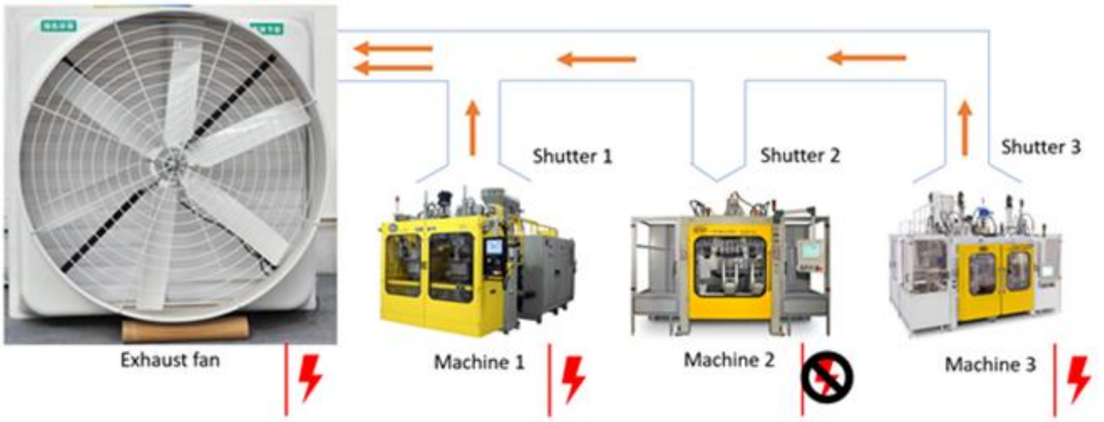

Figure 12. Main part of extended system

Figure 12 shows an exhaust fan device, which consumes electricity when it is working and exhausts air from three machines, when their shutters are open. In the example shown in Figure 5, the first and the third shutter are open, the second shutter is closed. If a shutter is open, then a partial electricity consumption of exhaust fan will be added to the related machine's electricity consumption data. If a shutter is not open, it means that the production machine is not in operation, so it does not need extraction and can be excluded from the calculation.

Improvements also had to be made in the cyberphysical system (its SCADA and database management system) to display our newly measured values. Then, in the SCADA system, we connected the extractors to the supported production machines, and this made it possible for the energy consumption of the extractors to be charged to the given production machines. With this, we can determine how efficient the operation of a particular extractor was during production [19][20].

In this section, the formula for the exhaust fans' partial electricity consumption will be defined. With our extended cyber physics system, we are now able to perform calculations in which we obtain energy consumption data that can be directly loaded onto the machines from the indirect energy consumption data of the exhaust fans. To achieve our goal, we need to know the partial electricity consumption of the extraction equipment for each shutter and production machine. We determined a formula that gives the partial electricity consumption to i^{th} shutter in each period (10-minute):

$$E_{S_i} = \begin{cases} \frac{E_{EX_j} * t_i * C_i}{\sum_{k=1}^{l} t_k * C_k} & \rightarrow if\ \exists k : t_k > 0 \\ 0 & \rightarrow otherwise \end{cases} \quad (1)$$

Equation (1) contains the following elements:

- E_{S_i}: The partial electricity consumption of the i shutter of j exhaust fan (kWh).
- j: Identification of the related exhaust fan.
- i: Identification of the related shutter.
- l: The number of shutters of j^{th} exhaust fan, and $1 \leq i \leq l$
- E_{EX_j}: The total electricity consumption of the j exhaust fan (kWh).
- t_i: The number of minutes (maximum 10), when the i shutter was open.
- C_i: The capacity of the i shutter (m^3/h).

After we get the indirect electricity consumption values (above), they are added to the related machines' electricity consumption values (below). Then we get the direct values, which contain the indirect (partial) consumption values:

$$E_i = E_{M_i} + E_{S_i} \tag{2}$$

Equation (2) contains the following elements:

- i: Machine (or shutter) identification (these are equivalent in this case).
- E_i: Direct electricity consumption (with indirect value) of i machine.
- E_{M_i}: Electricity consumption (without indirect value) of i machine.
- E_{S_i}: Indirect electricity consumption value of i machine.

The SCADA system was extended with equation (1) and (2), which was implemented in the form of programming. Thanks to our calculations, we obtained the direct energy consumption values.

The system will include large machine lines connected to an exhaust fan via not just one, but several (the maximum number will be 20 in 2022) shutters. In such cases, the indirect fractional consumption will first be summed and then the sum added to the direct consumption of the machine. In this case, equation (2) is modified as follows:

$$E_i = E_{M_i} + \sum_k E_{S_{j_k}} \tag{3}$$

Equation (3) compared to equation (2) j^{th} contains the partial consumption of all.

3. Results and discussions

After the introduction of data collecting and analysing methods, the related results will be discussed in this section.

3.1. Water consumption: examination of the amount of water used during fire service control

As we introduced the related method in the section 2.1, one problem of the data has been identified while monitoring the company's water consumption.

It is a national fire safety requirement and rule that all companies (not just industrial companies) should have the possibility to carry out fire safety inspections and fire drills. Consequently, the amount of water used for fire drills in the factory area is separate from the amount of water used for measurement. These exercises usually take place several times in the spring and summer months. During the research period, fire service water consumption was largely consistent, but there were occasional outliers. One of these events took place in May 2018, where we proposed an actual operative intervention with the help of our data collection. This period and event are illustrated in Figure 13.

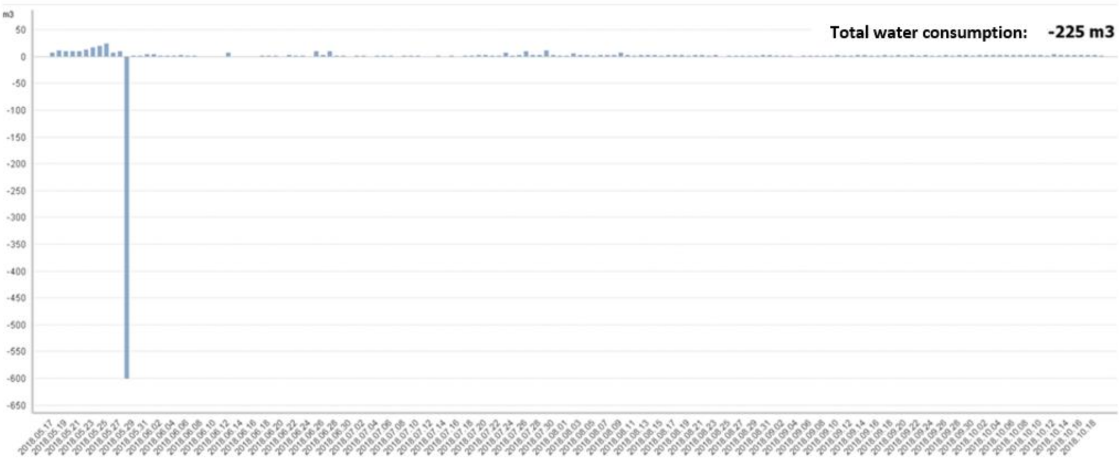

Figure 13. Fire service water consumption from May to October 2018

Figure 13 shows that at the beginning of the examined period, the amount of water consumption gradually increased, while there was no firefighting practice. Two possibilities have been identified as causes of the unjustified water use: one is the existence of a broken pipe and the other is a malfunctioning meter. The second solution was the correct one, the malfunctioning meter had sent false data to the system. The faulty meter was then replaced, and it was found that the new meter had a lower initial value than the old one, but this "error" could be corrected simply by overwriting the negative initial value in the database. After that, the data from the water use by fire service was consistent. The extension of our system also helped to solve the problems detected in water consumption, as we now knew and displayed not only one data per day, but 144 data per day.

In this way, the data problem related to the water consumption can be easily eliminated with the cyber-physical system.

3.2. Results related to energy consumption and compressed air emissions of compressors

In the section 2.2.1, the method of using compressors in the factory was introduced. In the following, we are focusing on the compressors useless and useful energy consumption in relation to their compressed air production.

We prepared several reports on the energy consumption of each compressor and the amount of compressed air generated. Such a report can be seen in Figure 14. In the figure, the horizontal axis is the date. The vertical axis on the left shows the energy consumption in kWh: these are the green and red bars. The green bars show the useful energy consumption, which for compressors means that they produced compressed air during the period. The red columns show the useless energy consumption when the compressors were running but not producing compressed air. The vertical axis on the right shows the amount of compressed air generated, which is illustrated by the blue dashed line on the graph. This value is given in Nm^3, which is the Normal Cubic Meter. Normal Cubic Meter means one cubic metre of Gas at reference conditions of 0°C and 1,01325 bar [18].

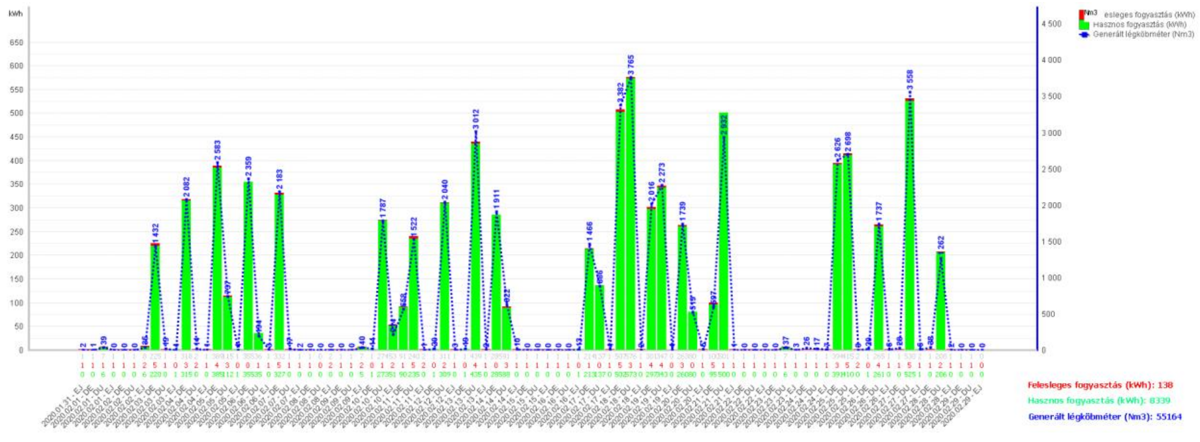

Figure 14. Compressor energy consumption and amount of generated compressed air in February 2020

The example shows that in February, the total volume of emitted cubic meters of air is 55,164 m3, the useful energy consumption is 8,339 kWh, and the useless consumption is 139 kWh. Where 0 values are visible, there were weekend days when there was no production, or another compressor was in operation. This compressor works quite efficiently as its useless power consumption is very minimal. In the database, we can also filter the periods down to 10 minutes, so we can examine the operation of the compressors even more precisely. Thanks to this, during our analysis we came across a compressor that did not work efficiently. The consumption data of this compressor are shown in Figure 15. It can be seen that this compressor had a much higher useless energy consumption, so it was on but not producing compressed air.

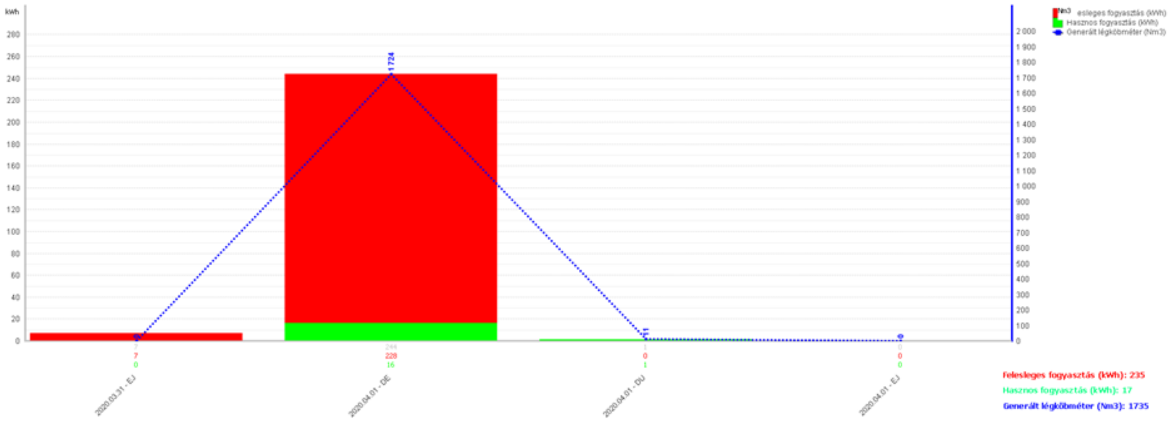

Figure 15. Consumption of an inefficient compressor broken down into shifts

This high level of useless operation could have been caused by breakdowns, neglect of maintenance, or simply by the people working on the shift being irresponsible and leaving the compressor on. We report our discovery to the company's management, who took the necessary steps to ensure the compressor was working properly.

The efficiency of compressors is mathematically described by the specific energy consumption index. Thanks to this, a new KPI was added to our system, which compares the consumption ratio of compressed air and electricity generated by a given compressor (Nm^3/kWh), so it shows how many cubic meters of compressed air a given compressor can generate using 1 kWh of electricity. The specific energy consumption performance indicator shows how efficiently the compressors use electricity. The following figures show the performance of a given compressor in a given period.

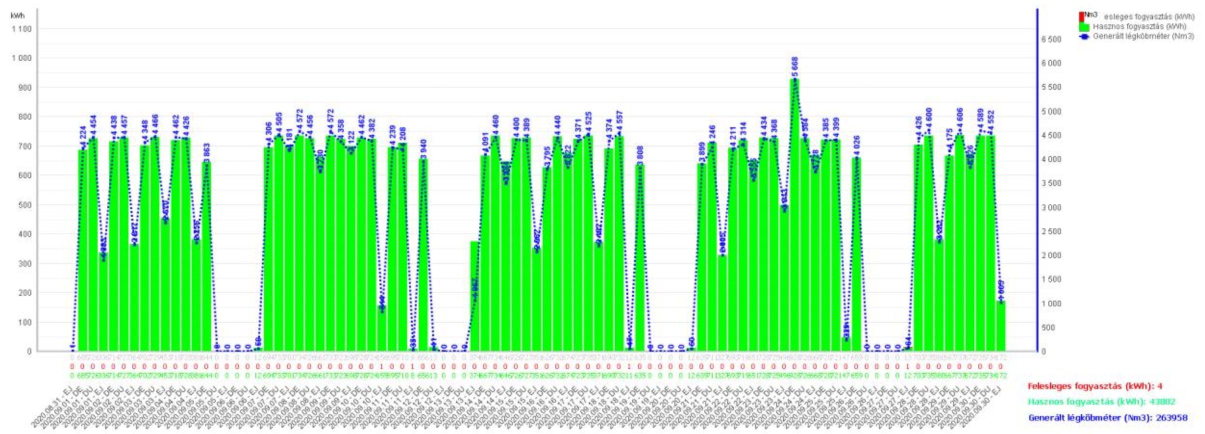

Figure 16. Energy consumption and amount of air cubic metres generated by a compressor in September 2020

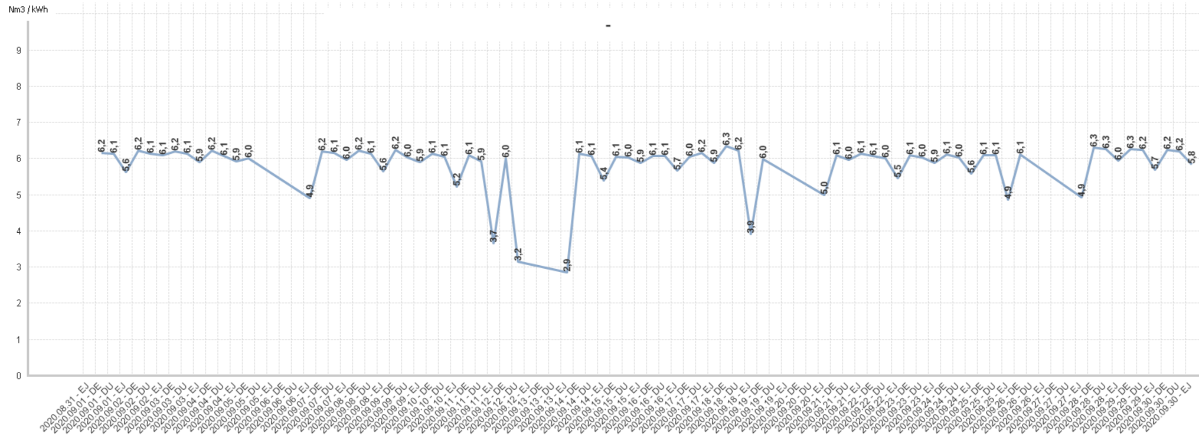

Figure 17. Specific energy consumption of a compressor in September 2020

Figure 16 and Figure 17 show the consumption of electricity and cubic meters of air and the specific energy consumption of one compressor of one plant. If we look at both figures, we can see that this compressor is working efficiently, as the performance indicator value is consistent during operation almost throughout the month. At 0 values, the compressor was not in use.

3.3. Exhaust fans energy consumption related results

In the section 2.2.2, the methodology was defined about the conversion of the extractors' indirect energy consumption (from the viewpoint of production) into direct values to the machines. In this section, a sample calculation will be introduced about the working about the extractors. After that, the data analysis' results will be presented about the live operation of the factory's extractors and their connected machines.

3.3.1. Illustration of methodology through a sample calculation

We provide a sample calculation with given and sample values. A given exhaust fan's constant values related to the shutters:

- Shutter 1 capacity [S1]: 36,550 m^3/h
- Shutter 2 capacity [S2]: 14,500 m^3/h

A given exhaust fan electricity consumption:

- In the first 10 minutes [T1]: 18 kWh
- In the second 10 minutes [T2]: 17 kWh

"Shutter 1 is open" status (we indicate the first 10 minutes with T1 and the second 10 minutes with T2):

- In [T1]: 2 min
- In [T2]: 4 min

"Shutter 2 is open" status:

- In [T1]: 3 min
- In [T2]: 5 min

Measured electricity consumption by machines:

- In [T1]:
  - E_{M1}: 25 kWh
  - E_{M2}: 10 kWh
- In [T2]:
  - E_{M1}: 30 kWh
  - E_{M2}: 13 kWh

Proportionate electricity consumptions of the exhaust fan per shutters and time frames (indirect consumption values): Substituting these values in equation (1), the following results are obtained:

- $E_{S1,T1} = 11.29\ kWh$ (Within first 10 minutes)
- $E_{S2,T1} = 6.72\ kWh$ (Within first 10 minutes)
- $E_{S1,T2} = 11.36\ kWh$ (Within second 10 minutes)
- $E_{S2,T2} = 5.64\ kWh$ (Within second 10 minutes)

Calculated direct electricity consumptions (machine) and indirect consumption values (exhaust) per time periods: Substituting these values in equation (2), the following results are obtained:

- $E_{M1+S1,T1} = 36.29\ kWh$

- $E_{M2+S2,T1} = 16.72\ kWh$
- $E_{M1+S1,T2} = 41.36\ kWh$
- $E_{M2+S2,T2} = 18.64\ kWh$

In this way, we get the direct electricity consumption values, which contain the indirect consumptions of exhaust fans.

The presented methodology has been validated in live operation: both the complex input data obtained during operation and our calculations have been verified and can be said to give correct results.

3.3.2. Results of real operational calculations

The results of the calculations are stored in the database every 10 minutes, and we have also extended the data displays of the production machines.

Figure 18 shows the electricity consumption of the machines and the sub-consumption data of the exhaust fans electricity connected to them. The data comes from one week in August 2020. We consider it important to first illustrate a report made from 2020 data, because at this stage of the research it was not yet possible to measure the operation of all the shutters in the plant. For this reason, the diagram shows "missing" (light green and light red) columns related to exhaust fans, highlighted with black square. In the diagram, the green bars represent the useful energy consumption during operation when the machines are producing products, so the operation of the machine and exhaust fan is profitable for the company. The red bars represent useless energy consumption when the machines did not produce products, therefore the operation of the machine and extractors is a loss for the company. For each column, the lighter green (useful) and the lighter red (useless) indicate the consumption values indirectly consumed by the extractors, and thus ultimately charged directly to the machine by our methodology. The numbers in blue represent the production volumes (m^2). Only the machines that were the largest consumers of electricity in a given week are shown in this graph. Figure 19 shows the corresponding metering values from Figure 18.

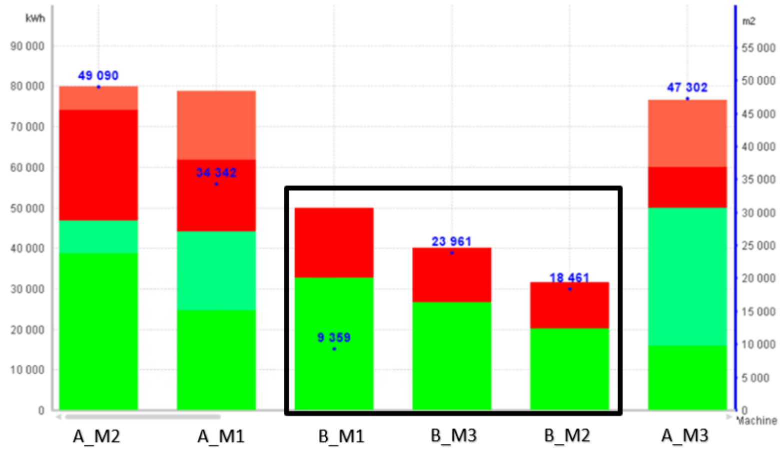

Figure 18. Useful and useless energy consumption of production machines and exhaust fans

Machine ID		A_M2	A_M1	B_M1	B_M3	B_M2	A_M3
Useless energy consumption (kWh)	Indirect extractor fan	5.781 41,5%	17.053 46,9%	0 0%	0 0%	0 0%	16.556 32,8%
	Indirect production machine	27.288 41,3%	17.748 41,8%	17.218 34,6%	13.462 33,6%	11.301 35,90%	10.151 38,9%
Useful energy consumption (kWh)	Direct extractor fan	8.155 58,5%	19.309 53,1%	0 0%	0 0%	0 0%	33.975 67,2%
	Direct production machine	38.713 58,3%	24.677 58,2%	32.573 65,4%	26.551 66,4%	20.180 64,1%	15.943 61,1%
Production volume (m²)		49.090	34.342	9.359	23.961	18.461	47.302

Figure 19. Measurement values related to Figure 18

After August 2020, the installation of new sensors for the shutters of additional extraction fans began. There are 6 exhaust fans working in the two plants of the company, 3 per plant. After the newly installed sensors provided enough data for further analysis to the database, we were able to prepare new analyses. The following figures (Figure 20 and Figure 21) show more recent statements relating to the consumption of extractors and production machines already in 2022.

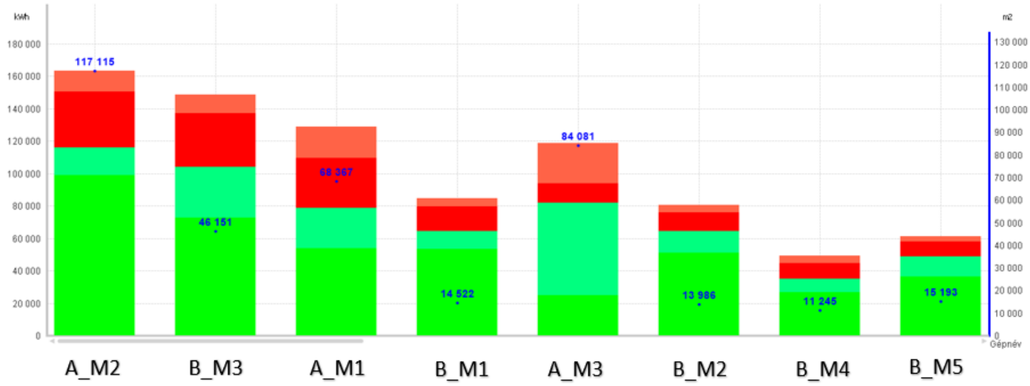

Figure 20. Useful and useless energy consumption of production machines and exhaust fans in October 2022

Machine ID		A_M2	B_M3	A_M1	B_M1	A_M3	B_M2	B_M4	B_M5
Useless energy consumption (kWh)	Indirect extractor fan	12.897 43,1%	11.166 26,4%	19.475 44,3%	4.932 30,5%	24.706 30,1%	4.565 25,9%	4.849 35,9%	3.207 20,3%
	Indirect production machine	34.272 25,7%	33.511 31,6%	30.835 36,3%	15.389 22,5%	11.823 32,4%	11.412 18,2%	9.316 26%	9.181 20,2%
Useful energy consumption (kWh)	Direct extractor fan	17.011 56,7%	31.080 73,6%	24.482 55,7%	11.248 69,5%	57.452 69,9%	13.032 74,1%	8.646 64,1%	12.602 79,7%
	Direct production machine	99.015 74,3%	72.654 68,4%	54.023 63,7%	53.134 77,5%	24.655 67,6%	51.291 81,8%	26.496 74%	36.360 79,8%
Production volume (m^2)		117.115	46.151	68.367	14.522	84.081	13.986	11.362	15.193

Figure 21. Measurement values related to Figure 20

Figure 20 shows the useful (green column parts) and useless (red column parts) energy consumption of the largest energy-consuming production machines and the exhaust fans that directly support them. The figures in blue are the total volumes (m^2) produced by the machines in one month. The main difference compared to Figure 18 is that much more machines are shown with their extractor sub-consumptions (light green and red). Figure 21 is a summary table showing the sub-consumption values and quantities produced (m^2) for each production machine and its associated extractor, as in Figure 19.

A new efficiency index has also been added to the system, which is related to the consumption of electrical energy of the hoods. The values in the Figure 22 diagram show how many kWh of electricity were consumed to produce 1 m^2 of wood (or piece of furniture). In the future, management may target a value to be kept to during production, but here again, it is worth considering, for example, the size of the timber and the power level of the machine while processing the workpieces.

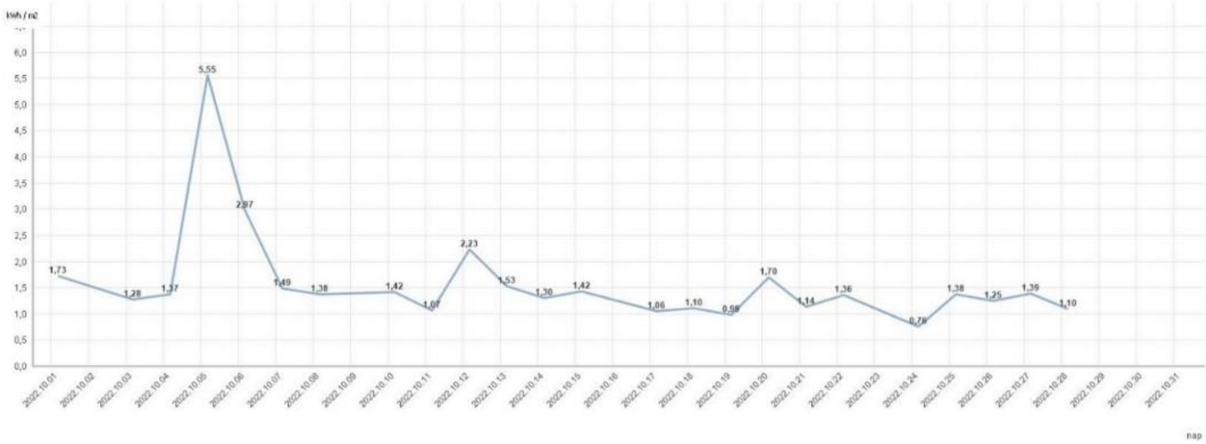

Figure 22. Specific energy consumption of machine A_M2 (kWh/m^2) in October 2022

Thanks to our research and development, we were also able to assign the related production machines to the individual exhaust fans in the system, and proportionally allocating the consumption of the exhaust fans to each associated production machine.

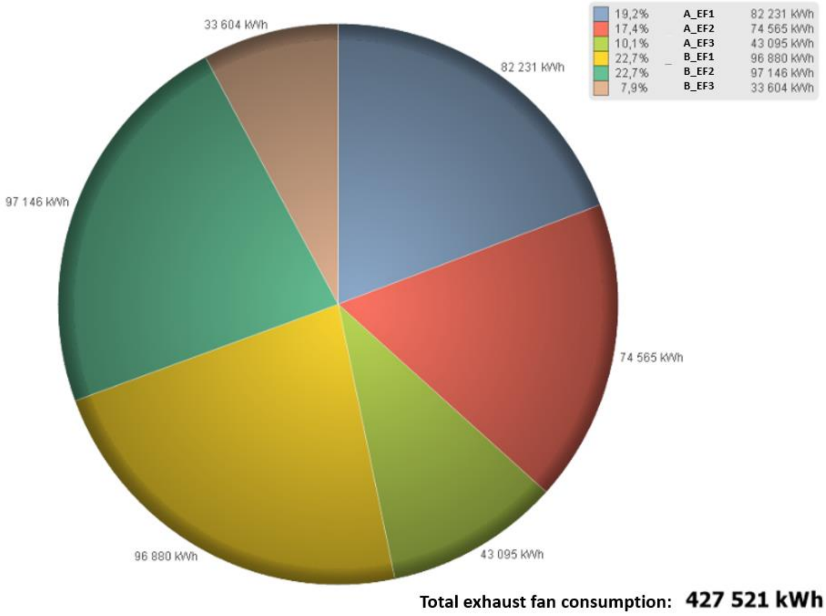

Figure 23. Total consumption of exhaust fans in October 2022

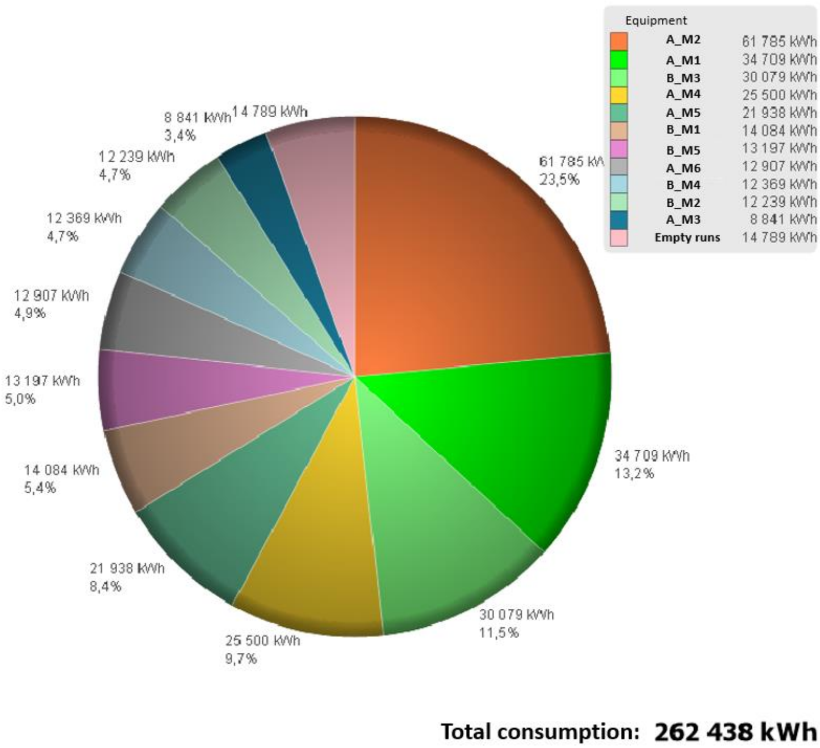

Figure 24. Exhaust fan consumption ratio by machines

Figure 23 shows all exhaust fans and their consumption in October 2022, while Figure 81 shows the consumption ratios of all exhaust fans projected onto individual production machines.

Figure 24 shows that the total consumption is much lower than the consumption of all exhaust fans (Figure 23). The reason for this is that not all exhaust fans (and all shutters) have yet been assigned production machines in the system, so these data are missing. In addition, the "empty runs" that are necessary, for example, to start and stop the extractors, must be taken into account. However, these are part of the technological process, since we cannot "save" the start-up and stop phases, which are associated with higher consumption for such large extractors.

Since the beginning of the research, we have achieved significant results with our work in relation to exhaust fans. However, the development cannot stop here, as there are still plenty of opportunities to carry out further research and obtain new results that are also useful for production. It is essential that each shutter of each extractor is equipped with a sensor, which is also connected to the cyber-physical system, and that the production machines missing from the system are assigned to them. A further objective could be to investigate the electricity consumption of the extraction fans for specific production processes and for specific types of wood, also in relation to the machines. If these developments were to be carried out in the future, it would be possible to reach a level where it would be possible to estimate very precisely the indirect cost of producing a specific product or group of products in terms of the electricity used [21][22].

3.4. Energy efficiency improvements for cost optimization and energy consciousness

In addition to monitoring the use of production resources (electricity, water, compressed air), it is important for us to achieve increasingly efficient, optimal factory operation and management. In addition, we can also fulfil an expectation that was pointed out to us several times as a shortcoming during our research: it was the presentation of electricity losses due to useless operation as concrete costs. This certainly constitutes an economic aspect of our research.

However, avoiding such wasteful activities, extra costs and losses can only work if we focus on energy consciousness in production. We assessed the circumstances of this and carried out a research and development project, as a result of which we encourage everyone from operatives working next to the machines to managers (and ultimately researchers) to operate more energy-consciously. To carry out this research, we have upgraded our cyber-physics system and are displaying to workers in near real time their own or other workers' energy efficiency.

Nowadays, energy consciousness plays an extremely important role in operations, which proves the relevance and importance of this part of our research [23].

3.4.1. The financial aspect of energy consumption

In Hungary, there is an Industry 4.0 model factory where production losses were measured in terms of the number of units of a particular brand of car, because the managers said that the workers were not able to estimate the amount of money that was being shared with them for information. In fact, nowadays a person who is not necessarily competent (i.e., not an electrical engineer or a professional) cannot imagine in real life what a loss of 10-100-1000 kWh might cost a company. For this reason, the sample company's managers saw it better to express the value of a car. Around 2015, the price of a car of that make was set at 2.5 million HUF, so if they wrote out that they had lost 4 cars for that year, which meant 10 million HUF. In order to be able to do the same for the furniture industry company, we must first know the amount of energy consumption expressed in HUF (or EUR). The situation is further complicated by the fact that we did not have to assess the losses incurred in production, but the deficits in resource management (mainly energy). We were able to use the cyber-physical framework presented earlier, but instead of business intelligence software, we used a self-developed web application to display the data and published and deployed it to the cloud.

As we are business informatics experts, it was definitely one of our goals to look at the financial side of resource use. We set another goal in this regard, which was to get to know the company’s financial losses resulting from the electricity consumption. In this way, much more tangible information can be provided to the company's employees than "just" how many kWh usages was useless (non-productive) during the periods (especially at the end of the months).

The application was based on the existing data collection and display framework. Losses due to electricity consumption were known at annual / monthly / daily / shift / 10-minute intervals, but the losses were only defined in kWh. The application can combine the collected 10-minute electricity consumption with the hourly rates received from the electricity provider. Since the prices are received in EUR, the application multiplies them with the daily exchange rate of the Hungarian National Bank, and in this way, we get exactly how many HUF each machine or piece of equipment wasted in a given month, day or even a shift. Example calculations made by the application are presented in the following figures. Since it is a test operation, we can only retrieve the data for a selected month (May 2020). During the development of the application, it was considered that the data for this one month was sufficient, as for research purposes it is not important for us to know what the electricity price was at that time, but to understand the structure of the data set. As a result, we were able to develop an application for it that can extract the values from it.

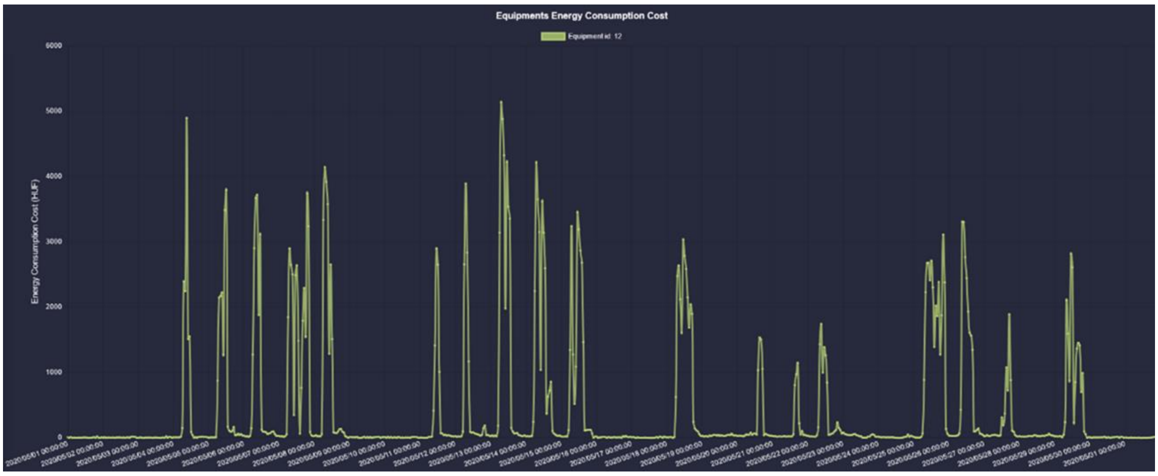

Figure 25. The costs of the operation of a selected production machine in a given month, broken down by hours

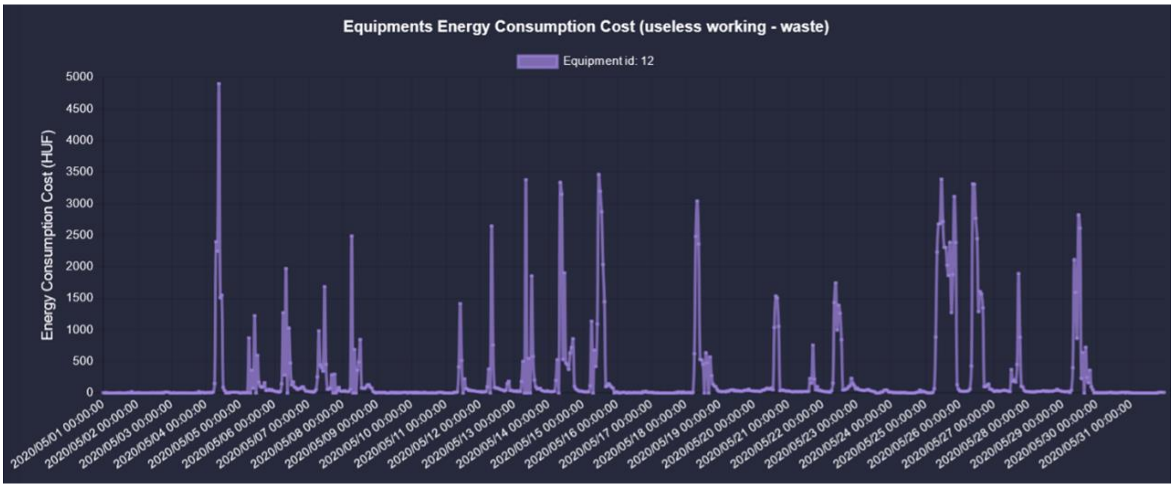

Figure 26. The cost of energy consumption of a specific equipment (with loss-making operation)

Figure 25 shows the cost of unprofitable operation of a production machine and its supporting equipment. It is noticeable that during this period it operated at a relatively unprofitably (Figure 26) compared to the total costs.

We have also examined the data from an economic and financial perspective, so that the consequences and costs of inefficient operation can be more easily understood by the company's management and even by its other employees.

3.4.2. Energy-conscious working in plants

In addition to achieving the objective of calculating the costs of unprofitable operations, we also started another task, which we also solved with a web application. This application checks, monitors and displays a key performance indicator that can inform the operators on the production line about their current performance and alert them if something is not right and needs their intervention. The key parameter we have chosen is the amount of kWh needed to produce one m^2 of furniture board, as this is the ratio that best describes the efficiency of production and the one for which we have measured data. For this ratio, a threshold value must be determined for each production machine, below which the performance can be considered unprofitable, and intervention is required or expected.

When we defined the main requirements for energy consciousness, the primary goal was to make the operators more energy efficient by paying more attention to their work, so that they could produce less wasteful operations and improve their energy efficiency. In practice, the subsystem is used to encourage workers to work more energy consciously [24]. This is also important because the company must comply with the ISO 50001 standard.

The application provides the possibility to see the values of the selected efficiency indicator (kWh/m^2) for the operator's machines in near real time. The system will continuously show the evolution of the indicator for the operator's machine and even alert him if it is not performing properly (for example: he should turn off the machine because it is not producing).

The appearance of the home page is simple and clean, as an operator must see the essence, they should not be distracted by any design elements, but the different colours will be important during use. The application works in near real time, which means that after logging in a production machine receives real performance indicators every 10 minutes, but here we have sped up the process and generate example data every few seconds to show the application in action. We have started an example run with example data that can illustrate both efficient and loss-making operation. Figure 27 shows the efficient operation.

Figure 27. Efficient operation (the value is above the limit)

Random values between 1-5 are generated for the efficiency ratios every 5 seconds. In the example, the limit was set to 2.5. It can be seen that the efficiency ratio was below the limit, but if the most recently measured values are correct, the kWh/m2 ratio is acceptable, then there is nothing special for the worker operating the machine. In Figure 28, we can already see a more wasteful operation (we switched the random number generation between 1-3). The operator can already see from the background colour of the application that he is operating the producer's machine wastefully, intervention may be necessary.

Figure 28. The latest ratio shows wasteful operation (below limit)

Figure 29 shows that the most recently measured values were below the limit, so it is necessary to intervene in the operation. The intervention may be to put the machine in a standby state or stop it, or start production, if possible. Here, in addition to the red background colour, the operator also receives a message warning him about wasteful operation. We have defined a threshold value (specifically three), which means that it still "accepts" indicators resulting from 3 measured values below the limit, so the background colour will only be yellow, but if a value below the limit is received after that, it will already turn red and the also a warning message.

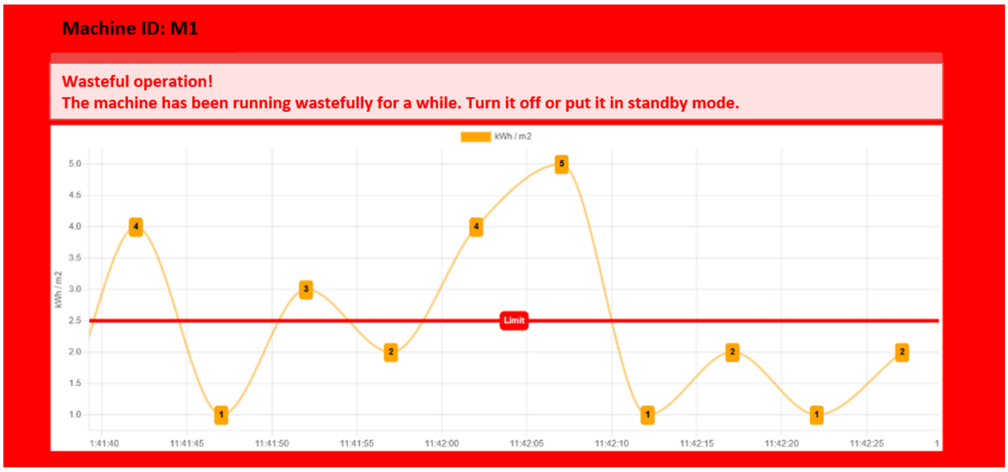

Figure 29. Indication of prolonged wasteful operation

Figure 30. Return to the correct operation

If the wasteful operation of the machine returns to an acceptable level above the limit, we automatically return to the default state and the operator no longer receives a warning (Figure 30).

Overall, it can be said that by developing the application, our common goal with the company was to try to get the operators to work more energy-consciously, thus achieving efficient operation with less energy loss. In addition, additional user groups (managers) also benefit from the development.

4. Summary

In the last few years, a cyber-physical framework has been implemented at a furniture manufacturing company to monitor in near real time the electricity consumption data related to machines and equipment. Where necessary, various calculations were used to convert indirect consumption into direct consumption, so that the consumption of the exhaust fans was passed on to the production machines and thus directly connected to production costs. By examining the water consumption on a daily basis, we discovered anomalies in the system and proposed solutions to them. From an efficiency perspective, we have also compared the compressors' production and consumption, so that they can be aligned with a new key performance indicator in usage in the company. We analysed the energy efficiency from several perspectives. First, we compared the consumption with the electricity prices and, especially for the useless consumption data, we highlighted how much unnecessary costs the unprofitable operation generated for the company. On the other hand, we focused on educating employees about energy consciousness. With the help of our application, a person operating a production machine can see in near real time how efficiently the machine he handled worked in the last 10 minutes. If the operation of the machine was not efficient, the application initially warns the worker about this, but if the wasteful operation continued, it suggested operative intervention.

We can continue the development of the system and, with it, the creation of further scientific results. This ensures progress towards better energy efficiency and optimal operation.

Acknowledgements

“SUPPORTED BY THE ÚNKP-23-4-II NEW NATIONAL EXCELLENCE PROGRAM OF THE MINISTRY FOR CULTURE AND INNOVATION FROM THE SOURCE OF THE NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION FUND.”

“The research was supported by the project No. 2019-1.3.1-KK-2019-00011 financed by the National Research, Development and Innovation Fund of Hungary under the Establishment of Competence Centers, Development of Research Infrastructure Programme funding scheme.”

References

[1] Dóra Horváth, Roland Zs. Szabó, Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?, Technological Forecasting and Social Change, Volume 146, 2019, Pages 119-132, ISSN 0040-1625

[2] Deloitte (2014): Industry 4.0 study, Deloitte Basel, Online, Available: https://www2.deloitte.com/content/dam/Deloitte/ch/Documents/manufacturing/ch-en-manufacturing-industry-4-0-24102014.pdf

[3] The 4th Industrial Revolution, Industry 4.0, Unfolding at Hannover Messe 2014, Online, Available: https://www.automation.com/en-us/articles/2014-1/the-4th-industrial-revolution-industry-40-unfoldin

[4] Krishnan, U. (2021). The Industry 4.0 and its associated technologies. Journal of Emerging Technologies, 1(1), 1-10.

[5] Cevikcan, E. – Ustundag, A. (2018): Industry 4.0: managing the digital transformation. Springer series in advanced manufacturing, Springer, 2018.

[6] 10 Trends That Will Dominate Manufacturing in 2023, Online, Available: https://global.hitachi-solutions.com/blog/top-manufacturing-trends/

[7] Mesumbe Bianca Epede, Daoping Wang, Competitiveness and upgrading in global value chains: A multiple-country analysis of the wooden furniture industry, Forest Policy and Economics, Volume 140, 2022, 102737, ISSN 1389-9341

[8] Deepak Kumar Jain, S. Neelakandan, T. Veeramani, Surbhi Bhatia, Fida Hussain Memon, Design of fuzzy logic based energy management and traffic predictive model for cyber physical systems, Computers and Electrical Engineering, Volume 102, 2022, 108135, ISSN 0045-7906

[9] Stefan Fischer, Claus Klammer, Antonio Manuel Gutiérrez Fernández, Rick Rabiser, Rudolf Ramler, Testing of highly configurable cyber–physical systems — Results from a two-phase multiple case study, Journal of Systems and Software, Volume 199, 2023, 111624, ISSN 0164-1212

[10] Alpár T.: „Gyártásszervezés támogatása a faiparban", IOT4U konferencia előadás, Budapest, 2016. december 6.

[11] Gludovátz A., „Termelési folyamatok felügyelete, irányítása és elemzése Ipar 4.0 megközelítésben", Doktori (PhD) értekezés, Soproni Egyetem Simonyi Károly Műszaki, Faanyagtudományi és Művészeti Kar, Sopron, 2018.

[12] Dimitris Mourtzis, John Angelopoulos, Nikos Panopoulos, Design and development of an IoT enabled platform for remote monitoring and predictive maintenance of industrial equipment, Procedia Manufacturing, Volume 54, 2021, Pages 166-171, ISSN 2351-9789

[13] R. Joppen, A. Kühn, D. Hupach, R. Dumitrescu, Collecting data in the assessment of investments within production, Procedia CIRP, Volume 79, 2019, Pages 466-471, ISSN 2212-8271

[14] J. Temido, J. Sousa, R. Malheiro, SCADA and Smart Metering Systems in Water Companies. A Perspective based on the Value Creation Analysis, Procedia Engineering, Volume 70, 2014, Pages 1629-1638, ISSN 1877-7058

[15] Yi Man, Yulin Han, Yifan Wang, Jigeng Li, Ling Chen, Yu Qian, Mengna Hong: "Woods to goods: Water consumption analysis for papermaking industry in China", Journal of Cleaner Production, Volume 195, 10 September 2018, pp. 1377-1388.

[16] Zakaria, Adel. (2015). Industrial ventilation. 10.13140/RG.2.1.3410.2241.

[17] Sűrített levegő tudásbázis, Online, Available: https://airmonitor.hu/suritett-levego-tudasbazis/

[18] CNG töltőállomások méretezése, Online, Available: http://www.cngport.hu/tudastar/cng-toltoallomasok-meretezese.html

[19] Simon Johnsson, Elias Andersson, Patrik Thollander, Magnus Karlsson, Energy savings and greenhouse gas mitigation potential in the Swedish wood industry, Energy, Volume 187, 2019, 115919, ISSN 0360-5442

[20] Waheb A. Jabbar, Thanasrii Subramaniam, Andre Emelio Ong, Mohd Iqmal Shu'Ib, Wenyan Wu, Mario A. de Oliveira, LoRaWAN-Based IoT System Implementation for Long-Range Outdoor Air Quality Monitoring, Internet of Things, Volume 19, 2022, 100540, ISSN 2542-6605

[21] Oscar Oliveira, Dorabela Gamboa, Pedro Fernandes, An Information System for the Furniture Industry to Optimize the Cutting Process and the Waste Generated, Procedia Computer Science, Volume 100, 2016, Pages 711-716, ISSN 1877-0509

[22] A. Al-Kababji, A. Alsalemi, Y. Himeur, R. Fernandez, F. Bensaali, A. Amira, N. Fetais, Interactive visual study for residential energy consumption data, Journal of Cleaner Production, Volume 366, 2022, 132841, ISSN 0959-6526

[23] Vasco Delgado-Gomes and José A. Oliveira-Lima and João F. Martins, Energy consumption awareness in manufacturing and production systems, International Journal of Computer Integrated Manufacturing, volume 30, number 1, 84-95 p., 2017, doi:10.1080/0951192X.2016.1185154

[24] Employee awareness of energy efficiency, Online, Available: https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-industry/energy-management-industry/employee-awareness-energy-efficiency/20411

About the Authors

Adrienn KONCZ received her PhD from the University of Sopron in 2023 in the field of material sciences and technologies. She is an assistant professor at the University of Sopron, Faculty of Wood Engineering and Creative Industries. Her research focuses primarily on Industry 4.0 technologies, energy management and industrial data analysis.

Attila GLUDOVÁTZ received his PhD from the University of Sopron in 2019 in the field of material sciences and technologies. He is an assistant professor at the Eötvös Loránd University, Faculty of Informatics. His research focuses primarily on data science, energy management and industrial frameworks.

