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

Adrienn Koncz

Thesis Booklet

Supervisors: Prof. Dr. Tibor László Alpár and Dr. Attila Gludovátz

University of Sopron

Jozsef Cziraki Doctoral School of Wood Sciences

Faculty of Wood Engineering and Creative Industries

Institute of Informatics and Mathematics

Sopron

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1. Introduction, motivations

When I started my PhD studies in September 2018, I had the opportunity to get involved in an IT research project in an internationally well-known furniture company. Starting in 2016, at the company has been developed a cyberphysical system, which is capable to collect, store and analyse electricity consumption data (either alone or combined with production data). The flow of data in this integrated system is based on the parameters measured by the sensors, which are transmitted either to the supervisory control and data acquisition (SCADA) system (electricity consumption data) or to the enterprise resource planning system (production data) via different internal IT networks. These data are analysed together or independently in an integrated way. We present the results to the local management (or the company's international managers) using a business intelligence application and its reports, which are understandable for all professionals and provide useful information to those examining the company's operation.

Before the start of my research and studies, the following main results were achieved: my supervisor and some relevant colleagues working at the company created a cyberphysical system for monitoring and supervising electricity consumption (with sensors, network, database, data display and analysis application). First, the electricity consumption itself was examined and predictive maintenance recommendations were made, later these electricity consumption data were linked to production performance (for example, how many kWh was used and how many units did a given machine produce). At this stage, I joined the research process, and my main objective was to monitor the company's use of all production resources, in addition to electricity consumption and production data. I planned to implement the supervision with the help of Industry 4.0 technologies, which the relevant employees of the company (manager, electrical, maintenance and safety engineer) were also open to in the technical department.

2. Research goals and expected results

Before starting my research, I identified the disciplinary gaps that my research will fill to move a furniture company forward to meet the challenges of Industry 4.0. Beyond the monitoring of production processes, the control and optimization of the use of resources directly and indirectly involved in production is a scientific subfield. So far, there has been little or no research in this area. I examine the use of resources not only by themselves, but often in combination, that is, how the operation of certain processes affects other areas within production. In addition to monitoring resources, I also look at their economic dimension, as a very strong motivating factor for research and development in this area is seeing how much unnecessary cost is involved in certain processes and how they could be made more efficient.

In addition to the configuration of the cyberphysical system, the previous results were mainly related to the use of electricity and production numbers. My main goal is to broaden this research spectrum and to extend the scope of the studies along the newly acquired data, as the data set, I have been able to work with is growing every year.

The new data mainly relate to the use of resources essential for additional production. However, this requires an expansion of the cyberphysical system, which involves data structure reconfiguration, the installation of physical devices, the networking of new measurement instruments and the use of more complex data visualisation and analysis tools.

These are the resources used in the factory, the use of which I will monitor and analyse: water (humidification, social water use, wastewater, fire service use), compressed air generated by compressors, the volume of air extracted by extractors in production machines. However, all this can only be considered as raw data that I can build on. To receive new types of data, the data structure needs to be transformed and expanded.

More complex studies based on basic (raw) data will provide much more complex information on the functioning of the factory, with deeper analysis and new key performance indicators (KPIs) to help me. For example, this will also highlight a weakness in previous studies, where the electricity consumption was only compared with production quantities. While the number of pieces may not be a good metric in this case. If we just think that a small piece of wood is also considered a piece, while a furniture panel with a diameter of several square meters, which is also a piece in the system, processing them may also require different kWh consumption from the production machine. Previously, this hidden problem was masked by the piece-kWh comparison, so a m^2-kWh comparison can give us much more information.

Regarding water use, consumption volumes and costs, I aimed to collect and display as detailed data as possible. This way, if there is a problem somewhere, such as a broken pipe, it can be detected much more accurately by the system.

Compressors, which generate compressed air for certain production processes for the machines, have also entered the monitoring system as a new element. My analysis are similar to the previous comparison of production volumes and electricity consumption for machines. I compare the amount of compressed air produced by compressors with the amount of electricity they consume. Using this new key performance indicator, I determine the ideal level of performance a compressor should maintain under normal, fault-free operation.

The energy consumption of the extraction fans was almost the same as that of the production machines during the periods under study. Thus, I also formulated the goal of “charging” the electricity consumption of the extractor fans to the machines that caused the extractor fan to operate. In this way, I can convert energy consumption and its costs, which can be considered indirectly related to production, into data directly related to production. This has many advantages for me, for example, in previous research, when I found that the machine was running at a loss, the new research now allows me to say that the amount of consumption of the extractor “charged” to it was also unnecessary. But the indirect cost of extraction calculated in this way - previously only estimated - can also be converted into a direct cost for the manufactured products.

3. New research results

In this section, I present my results achieved during the research and the related theses.

3.1. Development of the cyberphysical 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 cyberphysical system. The development of the cyberphysical 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 (extractor 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 [1]. 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 extractor 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 extractor 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 extractors are indeed the biggest energy consumers, but that the consumption of compressors is also significant. Figure 1 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 extractor 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 extractor fans were consuming so much, we had new goals for the research. Initially, it was not possible to relate the electricity consumption data of extractor 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 extractor fans, useful electricity consumption means that the extractor fan was running while the machines were producing products; useless electricity consumption means that the machines were not producing any products while the extractor fan was running. To convert indirect costs into direct costs, a number of modifications and extensions to the cyberphysical system were necessary [2].

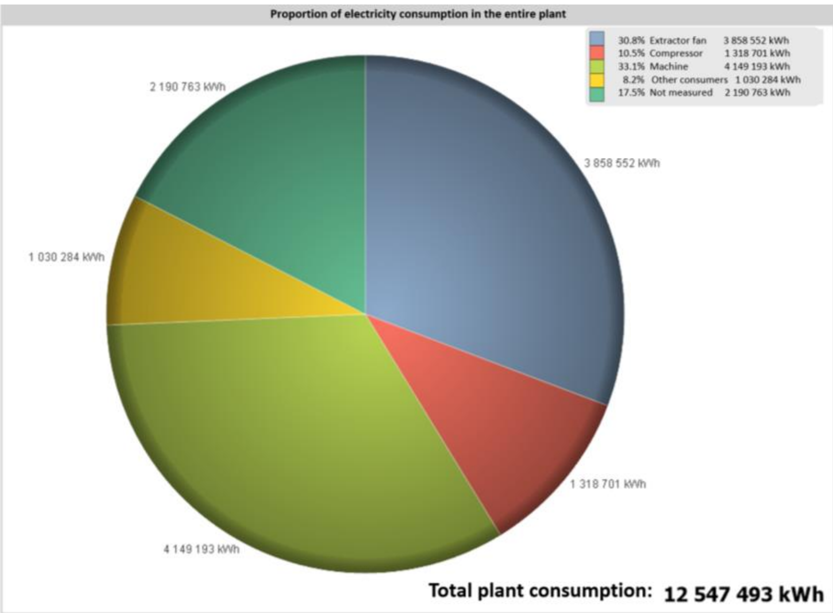

Figure 1: Electricity consumption in 2020

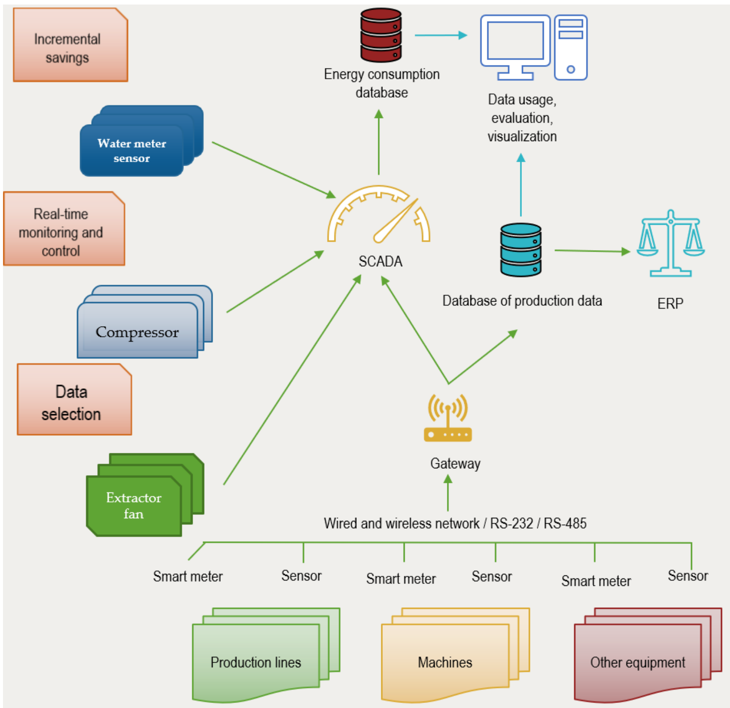

Figure 2: Construction of the extended cyberphysical system

Figure 2 illustrates the architecture of the extended cyberphysical 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 [3]. 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 3), 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.

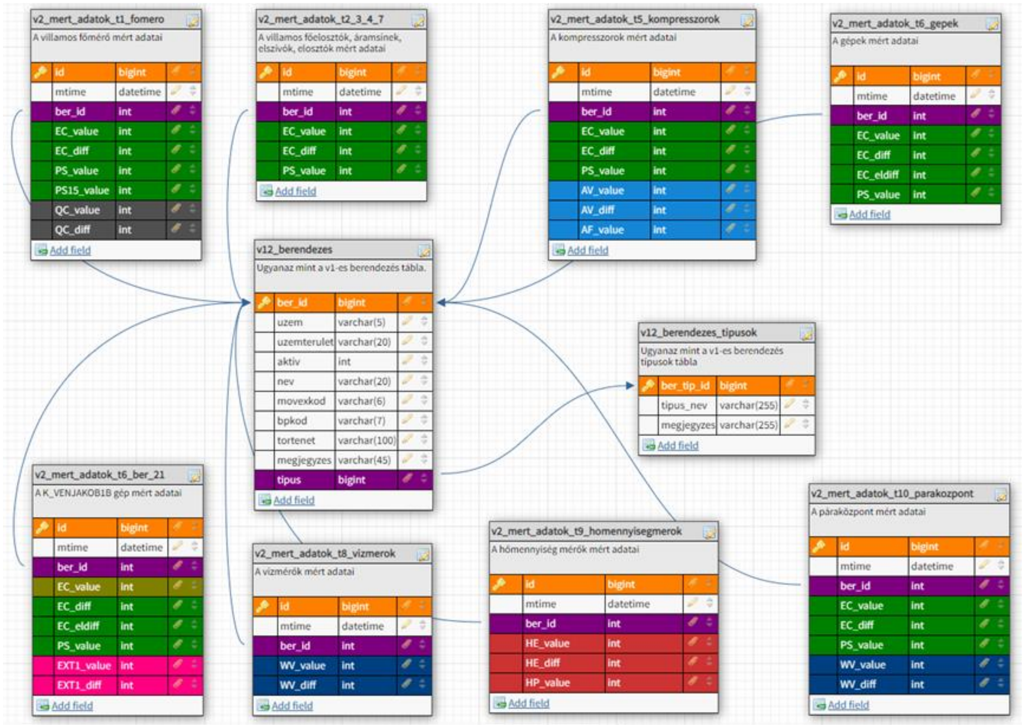

Figure 3: Database structure from 2021

Thesis 1: An extension of a cyberphysical system has been developed to monitor and control not only electricity consumption, but also other resources used in production (e.g., water consumption, compressed air produced by compressors and exhausted air from exhaust fans).

Related publications:
Journal article(s) in English: **[J2]**
Conference article(s) in English (abstracts, presentations, papers): **[C1], [C4], [C5]**
Conference paper(s) in Hungarian **[P2]**

3.2. Monitoring of water consumption

In connection with the monitoring of the company's water consumption, we have developed a data collection system that receives data on the amount of water consumed every 10 minutes. This enables us to produce detailed reports that can be used to identify potential problems such as pipe breaks or other water leaks. Specific examples include burst pipes and faulty sensors at the fire hydrant, but the system has also helped to identify the problem of water consumption in the fire hydrant itself (location of physical devices in the metering process). Compared to the previous daily data, we can identify problems in 10-minute increments, resulting in an accuracy of 144 times the once-a-day accuracy previously used. Not to mention that the daily aggregated data could potentially mask these errors or make them harder to identify [4][5].

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

Compressors are the third largest consumers of electricity in the company, so we thought it important to examine them. By generating and emitting compressed air, compressors support the operation of manufacturing machines in certain stages of production. For compressors, we have set several goals in terms of research. One of the goals was to expand the system both in hardware and software, that meant installing sensors on the compressors to measure the amount of compressed air and electricity consumption of each compressor. The hardware upgrade was necessary because initially only the compressor housings (Figure 4) were equipped with sensors that measured the total electricity consumption of all compressors.

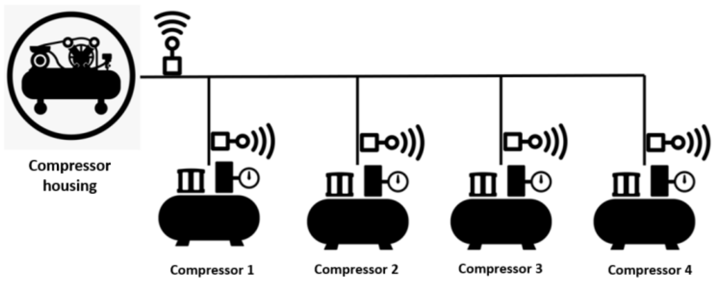

Figure 4: Construction of a compressor housing

Based on the data saved with the help of the SCADA system, we also wanted to monitor the consumption values in the business intelligence system, so we had to make changes in the system so that the efficiency (useful/useless) measures are displayed in addition to the consumption data for the compressors. Our other goal was to create a new KPI that compares the number of cubic meters of air produced by compressors to their electricity consumption. This will show to us how much kWh of electricity a given compressor uses to generate one m^3 of air. This indicator is important because it allows to define, for each compressor, the ideal performance values that it should maintain during normal, efficient, and fault-free operation [6][7][8].

Thesis 2: I examined the resources supporting the production both by themselves (water consumption) and in comparison, (in relation to compressors, I examined the compressed air produced and the electricity consumed together) with each other. As a result, in many cases I discovered anomalies in the process of use and operation, that can be eliminated later.

Related publications:
Journal article(s) in English: **[J2]**
Conference article(s) in English (abstracts, presentations, papers): **[C3], [C4], [C5]**
Conference paper(s) in Hungarian **[P2]**

3.4. Extractor fans energy consumption related results

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.

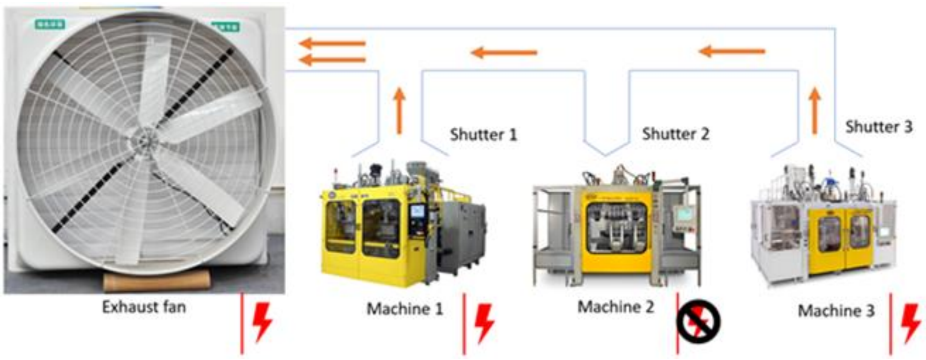

Figure 5: Main part of extended system

Figure 5 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 [9][10].

3.4.1. Formula for partial electricity consumption

With our expanded 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 extractor 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:

$$E_i = E_{M_i} + E_{S_i} \quad (2)$$

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 extractor 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:

$$E_i = E_{M_i} + \sum_k E_{S_{j_k}} \quad (3)$$

Equation (3) compared to equation (2) j^{th} contains the partial consumption of all (*k* pieces) of extractor fans calculated for the shutter that is i^{th} connected to a machine line.

3.4.2. Illustration of methodology through an example 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.

Thesis 3: The second largest energy-consuming equipment in the factory, closely following the production machines, are the extractor fans. I am able to analyse their electricity consumption using a proprietary methodology (involving hardware, software and algorithmic improvements). Thus, I calculate direct consumption quantities from indirect uses. This allows me to determine the losses of useless operations much more accurately.

Related publications:
Journal article(s) in English: **[J1]**
Conference article(s) in English (abstracts, presentations, papers): **[C2]**
Conference paper(s) in Hungarian **[P1]**

4. Utilization possibilities of achieved results

The existing cyberphysical system with all its components can be used at any other subsidiary of the company involved in the research, but also at other production companies, irrespective of size and profile. If a company is going to need a similar system in the future, it is first necessary to understand the company's operations and processes, especially the production and the equipment and tools that support it. In addition to understanding the processes, it is necessary to determine what sensors are needed to create the hardware environment for the cyberphysical system. The communication network between the devices must be developed, as well as the hardware environment for data collection. If the hardware environment has been successfully installed, the software environment can be created afterwards. There are several options available for this, on the one hand, the company can purchase boxed software, and on the other hand, it can use individually developed applications designed to its own processes and devices.

If the hardware and software environment of the cyberphysical system is completed, the data collection and analysis solutions are already available. This can be followed by the interpretation of the goals set during the consultation with the company's specialists and the assessment of their feasibility. According to the priorities of the company's managers (what they want to improve), the next step is to compile data collection and analysis plans. Based on the objectives to be achieved, the database plan, which can be considered universal, needs to be fine-tuned according to the needs of the specific company environment. For example, if the company does not use compressors, we will not compare the amount of air cubic meters with electricity, but the data of the equipment they use to support production. So, first we need to identify the key performance indicators (KPIs) that can be applied there, for which we need to start collecting data. In this way, over time, company managers will have more and more useful information about their overall operations through KPIs and can set targets in which they want to move forward, to become better and more efficient.

5. List of publications

Journal articles in English

[J1] Adrienn Koncz; Attila Gludovátz: Calculation of indirect electricity consumption in product manufacturing, International Journal of Energy Production and Management 6: 3 pp. 229-244. Paper: 10.2495/EQ-V6-N3-229-244, 15 p. (2021)

[J2] Adrienn Koncz, Attila Gludovatz: Efficient energy management system and optimization of resources at a furniture company, SEFBIS JOURNAL 2019: 13 pp. 72-83., 12 p. (2019)

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[C1] Adrienn Koncz, Attila Gludovátz, Gergely Bencsik: Smart analyses in the era of Industry 4.0, In: Bacsárdi, László; Bencsik, Gergely; Pödör, Zoltán (szerk.) OGIK 2018: 15. Országos Gazdaságinformatikai Konferencia - Az előadások összefoglalói, Sopron, Magyarország: Alexander Alapítvány a Jövő Értelmiségéért (2018) 88 p. pp. 49-51., 1 p.

[C2] Koncz Adrienn, Gludovátz Attila: Indirect electricity consumption calculation in the product manufacturing, In: Zoltán, Horváth; Adrian, Petruşel (szerk.) Collection of Abstracts: 13th Joint Conference on Mathematics and Informatics, Budapest, Magyarország: ELTE Informatikai Kar, Babes-Bolyai Tudományegyetem, Babes-Bolyai Tudományegyetem, Matematika és Informatika Kar, Babes-Bolyai Tudományegyetem (2020) 201 p. pp. 100-101., 2 p.

[C3] Gludovátz Attila, Koncz Adrienn: Efficient energy management system at a furniture company, In: Bacsárdi, László; Bencsik, Gergely; Pödör, Zoltán (szerk.) OGIK'2018 Országos Gazdaságinformatikai Konferencia - Válogatott közlemények, Sopron, Magyarország: Alexander Alapítvány a Jövő Értelmiségéért (2019) 92 p. pp. 43-47. Paper: OGIK2018-K-5, 5 p.

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[C5] Adrienn Koncz, Attila Gludovatz: Resource management with IoT devices at a wood industrial company, In: Raffai, Mária; Honfi, Vid (szerk.) OGIK'2019 16. Országos Gazdaságinformatikai Konferencia, (2019) pp. 49-50., 2 p.

Conference papers in Hungarian

[P1] Koncz Adrienn, Gludovátz Attila: Termelő vállalatnál telepített IoT-alapú energiafelügyeleti rendszer kiterjesztése, In: Molnár, Dániel; Molnár, Dóra (szerk.) XXIV. Tavaszi Szél Konferencia 2021 Tanulmánykötet II., Budapest, Magyarország: Doktoranduszok Országos Szövetsége (DOSZ) (2021) 755 p. pp. 52-66., 15 p.

[P2] Koncz Adrienn, Gludovátz Attila: Energiafelhasználás és további erőforrások optimalizálása egy bútoripari vállalatnál, Tavaszi Szél – Spring Wind 2019 II. kötet pp. 542-556., 15 p. (2020)

Other publications

[C6] Koncz Adrienn, Gludovátz Attila, Analysis of Resource Consumption Using Cloud Services in Industrial Environment, In: Raffai, Mária; Kosztyán, Zsolt Tibor (szerk.) OGIK'2021 Országos Gazdaságinformatikai Konferencia, Veszprém, Magyarország: Platina Nyomda és Kiadó Kft. (2021) 64 p. pp. 26-27., 2 p.

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[9] 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

[10] 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