Grishkina Anastasiia

Application of digital twin technologies for the optimisation of the energy consumption for a wood clattering panels manufacturer

School of Technology and Innovation
Master's thesis in Industrial Management
Programme

Vaasa 2023

UNIVERSITY OF VAASA
School of Technology and Innovation
Author: Grishkina Anastasiia
Title of the Thesis: Application of digital twin technologies for the optimization of the energy consumption for a wood clattering panels manufacturer
Degree: Master of Science in Business Administration and Economy
Programme: Industrial Management
Supervisor: Rayko Toshev
Year: 2023 **Sivumäärä:** 106

ABSTRACT :
This thesis describes applications of digital twin technology for the optimization of the energy consumption profile. It is based on the electricity consumption data from a Finnish wood clattering panels manufacturer – Puucomp. The data consists of hourly records for the duration of 36 months. Production simulation was used to identify the bottleneck process with the highest energy consumption, which is perforation. The Energy Value Stream Mapping (EVSM) method may be enriched with the digital twin (DT) models and electricity data, enabling energy flow tracking at the current time.

It has been determined that the highest energy consumption occurs during the morning hours, with an overall increase in consumption during the cold period. The data has not shown significant dependency on humidity, wind speed, or air pressure. The base load has been considered with the floor heating and the gap required to fulfill is 60kWh.

Proposed solutions are utilization of renewable energy sources, technological improvement of the systems, and production rerouting. The most viable solution is the energy mix, which includes renewable energy sources used with the combination of energy storage systems (ESS) in the form of batteries. The first scenario consists of the utilization of rooftop space for the solar panels, which are expected to support floor heating, while ESS is used to support the grid during peak hours. The second possible scenario includes rooftop leasing, geothermal heat pump utilization for the floor heating and ESS as a support to the grid.

Utilization of DT technologies has been seen as a viable approach to reduce energy consumption profile. However, the application of DT is limited by the availability of the data.

KEYWORDS: Digital twins, production systems simulation, energy consumption optimization

Contents

Figures

Tables

Abbreviations

ABS – Agent Based Simulation

ASHP – Air Source Heat Pump

CAD – Computer Aided Design

DES – District Event Simulation

DT – Digital Twin

EAHP – Exhaust Air Heat Pump

EnMS – Energy Management Systems

ESS – Energy storage management

EVSM – Energy Value Stream Mapping

GSHP – Geothermal Source Heat Pump

HAWTs – Horisont Axis Wind Turbine

HVAC – Heat Ventilation and Air Conditioning

ISO – International Organization for Standardization

JIT – Just in Time

MCS – Monte-Carlo Simulation

MPS – Manufacturing and Production Systems

PDCA – Plan, Do, Check, Act cycle

PLC - Product Life Cycle

PV – photovoltaic

QM – Quality Management

SAHP – Solar Assisted Heat Pump

SCM – Supply Chain Management

SD – System Dynamics

SMEs – Small and Medium Enterprises

TQM – Total Quality Management

VAWTs – Vertical Axis Wind Turbine

VC – Visual Components

VSM – Value Stream Mapping

1 Introduction

The need for the reduction of energy consumption as well as the increase in the use of renewable energy sources has been rising over the past 20 years. However, the problem of energy consumption and growth of the electricity prices has been even more relevant in the past few years. This situation has been pushing companies to seek for solutions to reduce energy consumptions as well as the costs of production. Energy utilisation by production in Finland has reduced by 6% between 2009 and 2020, according to statistics (Official Statistics of Finland (OSF), 2020). The price of electricity yet has doubled in the last quarter of 2021 (Official Statistics of Finland (OSF), 2020). The energy consumption reduction does not meet with the drastic price growth. Along with cost reduction, the sustainability of manufacturing solutions and their impact on the environment should be considered.

Companies are gradually incorporating smart manufacturing technologies, such as industry 4.0, to enable production optimization and more cautious resource utilization. One of such resources is basic electricity. Data from International Energy Agency report (IEA, 2022) indicates that as of 2021, 28% of the world's electricity supply comes from renewable sources. The main trend for 2050 is to increase share of renewable energy production up to 60% of global energy supply. Despite the visible growth of the renewables, share of the non-renewable energy production remains significant. (IEA, 2021)

The application of digital twins has typically been made for and by businesses to maximize production, monitor the overall condition of the machinery, staff training, and plan for new construction and demolition. Additionally, the benefit of digital twin technology lies in the enhancement of the customer experience. However, due to the high cost of the technology and equipment needed for the construction of the twin, only large and medium-sized businesses have been able to utilize digital twins fully. Despite the cost and lack of availability of the technology previously it may be one of the most efficient solutions for tracking and change in energy utilization both environmentally and economically. Nowadays, digital twin technologies become more accessible in terms of pricing and development.

1.1 Research gap – research area

Previous studies have been focused on resolving energy utilization issues with mainly one direct approach and one emphasis area. The research gap can be found (Figure 1) between several areas: sustainability, environmental impact, digital twin (DT) and simulation of production. The research area of this thesis focuses on the energy optimisation solution development for a Finnish wood clattering panels manufacturer. One novel approach for the energy utilization optimisation is DT concept. DT is deeply connected with the energy sector and sustainable development, digital transformation, and digital twin technologies.

It investigates the opportunities for energy consumption optimization. From the perspective of the simulation of production systems and DT the solutions to be looked for are focused on the technological advancement of the matters concerned with the production. Following that, the methods for integrating and delivering solutions within a company could be examined using Sustainability and Lean management practices. While the sustainability of production may not be the biggest concern of SMEs, in a longitudinal time frame sustainable solutions have been shown to affect energy utilization positively. The energy optimisation area delivers an understanding of the utilization of energy by machinery, appliances, and HVAC (heat, ventilation, and air conditioning) as well as its generation and allocation matters. Moreover, energy optimisation focuses on the estimation of the energy efficiency of components within an enterprise.

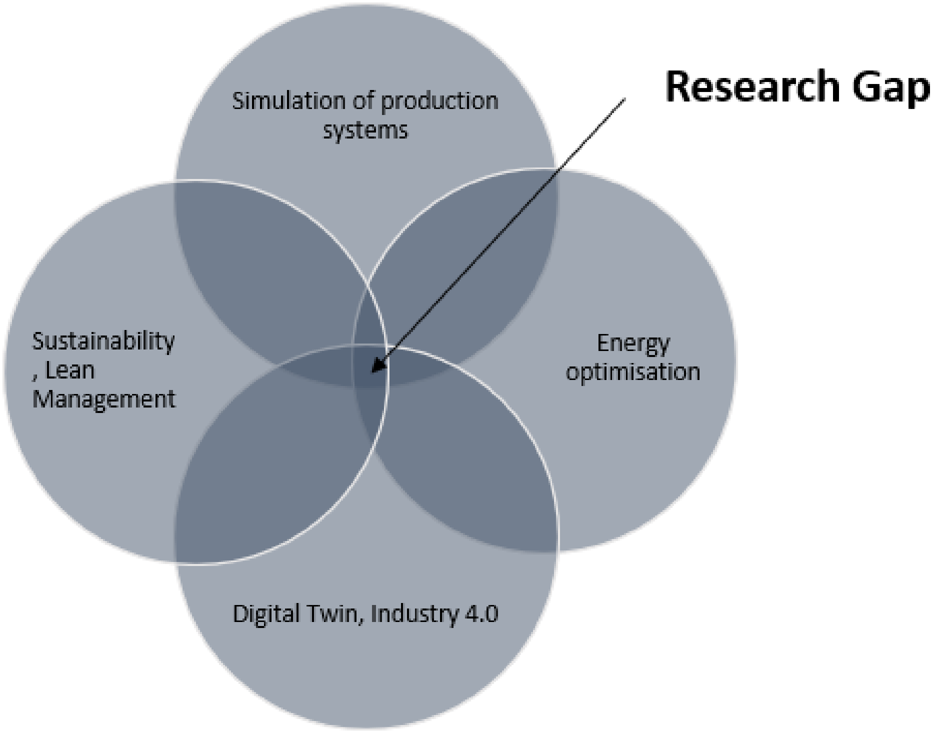


Figure 1 Definition of the research area

Additionally, the study strives to investigate alternative (renewable sources) and mixed solutions (combination of several renewable energy sources with e.g., energy storge) to propose the most viable result for the case company. Next, there are steps to be taken:

- Study the application of the digital twin for the energy optimisation case
- Handle the simulation of the production in order to visualise bottlenecks
- To analyse the energy consumption data set, definition of the seasonality
- Research on the alternative solution for the existing one
- Proposal of the solution
- Use of the sustainable development practices throughout the project

1.2 Sunders' onion framework

An essential component of the thesis is the research methodology, which ensures that the methods, tools, and underlying philosophy are all consistent. Saunders (2007) formed one of the well-known research design frameworks, named "research onion". The Saunders research onion (Figure 2) consists of six layers, following which the scholar is moving from the outer core to the inner core formulating logical research structure. The outer layer is the research philosophy, followed by next layer – approach to the theory development. Next layers are focusing on the selection of the methodology, strategy and the time horizon. Finally, the most inner layer is the techniques and procedures for the data collection and the analysis. (Saunders et al., 2019)

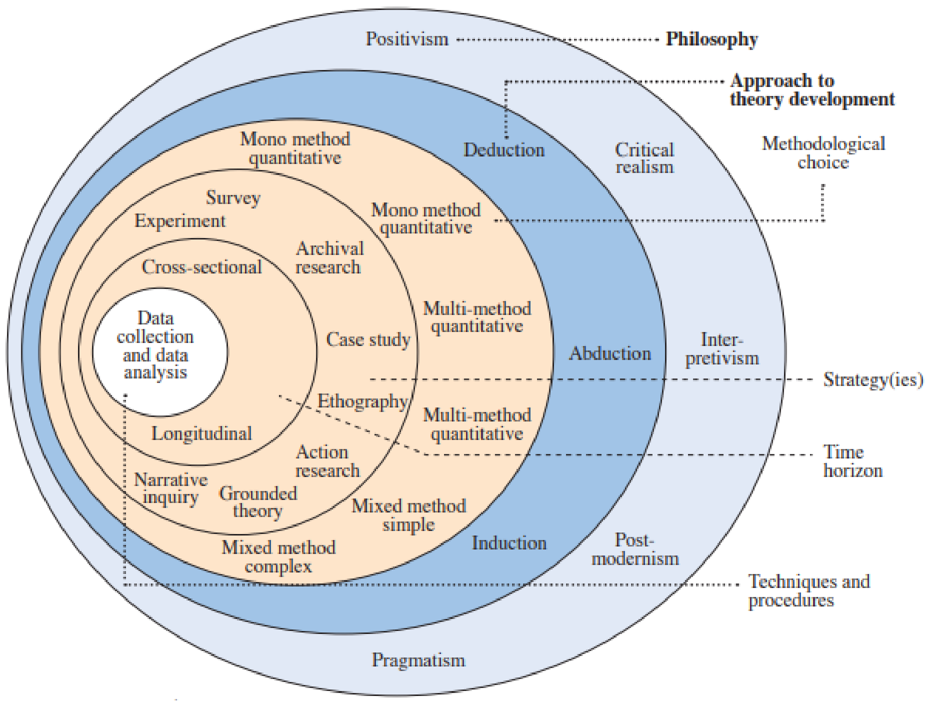


Figure 2 Saunders research onion (Saunders et al., 2007)

1) Research philosophy

The research philosophy delineation is the first layer of the Saunders' research onion. The research philosophy according to Saunders et al., is a set of beliefs and assumptions used in the knowledge formation (2019). There are several assumptions upon which the research is built - epistemological, ontological and axiological assumptions. The ontology and epistemology are more commonly applied in the research. Ontology – is focused on the nature of being, striving to recognise the certainty of the knowledge about the objects. In other words, testing the knowledge of the actually existing things in the world, that humankind is able to study (Saunders et al., 2019). Epistemology – on the other hand is “study of knowledge” and it strives to understand the limits of the knowledge, relying upon different sources and data. Epistemology includes positivism, interpretivism and pragmatism philosophies.(Al-Ababneh, 2020)

In this study the pragmatism/ positivism philosophy has been applied. Positivism philosophy does not involve personal opinions and is based on the observations and assumptions. In other words, the knowledge in positivism is acquired through empirical research. Pragmatism philosophy acknowledges the numerous approaches to understand the researched question as well as to conduct research on the matter. However, it indicates that there is no one single approach to the problem that can provide with a full understanding. According to the question's origin, pragmatic research is built around it and may incorporate elements of positivism or interpretivism. (Saunders et al., 2019)

2) Approach to the theory development

The second layer is the approach to the theory development. There are two approaches to the theory development – deductive and inductive. According to the work of Canlas & Karpudewan (2020) inductive approach starts with a collection of factual observations, looks for patterns, and then theorizes about those patterns. The deductive approach on another hand is starting with a theory, then the hypotheses are formed, followed by evidence collection and assumption analysis (Saunders et al., 2019). Generally, both inductive and deductive approaches can be applied within one work by the scholar in order to build richer knowledge basis.

In this thesis mainly inductive approach has been applied. The research begins with the analysis of the energy data from the case company. Next, the study is built upon the existing studies about the simulation of production, digital transformation as well as energy issues for the production. This focus lies in the examination of prior studies, evaluate and access the strategy in order to address the issues within a case study.

3) Research strategies

Next layer is the research strategy. This work is based on the case study, which is already defining the strategy applied in it. The specifics of the case study lie in the conducting of an in-depth investigation of the real-life setting (Darke et al., 1998).

4) Research choices

The research choices layer is responsible for the methods applies in the research. There are three different type of research methods – mono method (qualitative or quantitative), mixed method and multi-method (Saunders et al., 2019). Qualitative research is based on the non-numerical data analysis- such as videos, interviews – forming opinions and concepts. Quantitative methodology, contrary, based on the analysis of numerical data, enabling formulation of the patterns, and forecasts in order to support of reject the hypothesis claims (Weyant, 2022). In quantitative research, data are gathered in order to quantify information and statistically analyse it in order to confirm or deny "alternative knowledge claims." (Creswell, 2003; Weyant, 2022)

The multi-method, thus the qualitative and quantitative methodology has been applied in this thesis work. The combination of the methodologies enables greater accuracy and in-depth study of the research questions.

5) Time horizon

The next layer is the selection of the time horizon of the research. Saunders et.al., (2019) notes that the time horizon is not depending on the selected research strategy. Generally, there are two types of time horizons - longitudinal and cross-sectional. Bryman & Bell, (2015) described cross-sectional timeframe as gathering information on several cases at the particular point of time. On the opposite, the longitudinal time horizon refers to the collection of the data over the multiple points of time (Bryman & Bell, 2015). In this study the data is collected over the longitudinal time horizon, taking into consideration data sets provided by the case company as well as from the simulations conducted during the project.

6) Data collection methods – techniques and procedures.

The last layer of the research onion is the techniques and procedures used for the data collection. The data collection and processing are dependable on the previous decisions in the research design process (Creswell, 2003; Weyant, 2022). The main purpose of the data is to answer research questions. The data collected could be divided into primary and secondary. Primary data sources are the data that is received from the case company and gathered throughout the handled simulations, whereas secondary data is observed from the prior studies.

1.3 Research questions

Research questions are derived from the research gap determined in the previous section. In order to produce a functional and viable solution within the given timeframe it has been decided to concentrate on the energy efficiency and flexibility of the solutions. An additional focus to research in the thesis work is the digital twin technologies implementation for SMEs.

Therefore, research questions have been formed as:

1. What is the energy consumption profile for the manufacturing of a wood clattering panels?
2. What solution can be used to minimize and optimize it?
3. Can Digital Twin concept be used in energy case?
4. What are the limitations of Digital Twin implementation for SMEs?

1.4 Case study, problem statement

The case studies focus on examining solutions for the optimization of the energy consumption for the manufacturing of the wood surface clattering panels used for the design of the interior. The main problem of the company's energy utilization has been allocated as the peak energy consumption in the morning hours. The start of the morning shift, when the majority of the machinery is switched on, may explain such a picture. In order to reduce peak energy consumption, the company has implemented capacitor batteries for the majority of the machines, however, the desired reduction in peak consumption has not been achieved. Moreover, the initially proposed solution of utilization of an additional energy storage for the morning hours hasn't been seen as feasible by the case company. The peak consumption of electricity is not only problematic from the cost perspective but also due to the lack of electricity in the grid. As a result, the solution should address potential electricity production issues as well.

The energy data set provided by the case company consists of the hourly records for the duration of 3 years. Provided data for the given time frame enables the production of viable results. The energy may be organized, visualized, and systematized. First of all, energy utilization fluctuations during the day need to be determined. The next step, after defining the peak energy consumption hours throughout the day, was to determine the seasonal changes in consumption. The goal was to see whether the heating during colder periods is rising overall energy consumption significantly. Additionally, the possibility of recuperation of HVAC systems has been discussed as some of the ventilation recuperation is already implemented on the shopfloor.

Some of the proposed solutions to look into:

1. Alternative energy source to basic electricity, such as renewable energy
2. Rerouting of the production line
3. Integration of additional energy storage batteries together with smart plant solutions
4. Integration of the mixed solution

The visualization of consumptions can then be used to determine the bottleneck and see if it is possible to prevent or reduce peaks by resolving those. In addition to the data set representation, the model of a shop floor is to be developed with consideration of the main machining and manual processes. The analysis of the simulation along with visualization of the data on the energy consumption enables the formulation of the basis for the development of the solution for the case company.

1.5 Structure

This work consists of six main chapters, following the research logic – introduction, literature review, methods, results, conclusions and discussion. The first chapter is focused on the background of the study, followed by the definition of the research area, formulation of the research questions and case study explanation. Next, the second chapter gives an overview of the most recent and relevant literature on the topic, defining the concepts used in the research. The methodology applied in the research is explained in chapter 3. Further, research results are presented in the fourth chapter. Finally, in chapter five the conclusions are underlined, and in chapter 6 further research suggestions are provided.

2 Literature review

2.1 Industry overview

2.1.1 Wood processing industry in Finland

The wood processing industry has been undergoing a transformation over a few decades. The use of wood-based products has been reduced as well as the location of the main forestry manufacturers has changed. It may be explained by the growth of the trend for more cautious resource usage. An additional reason for the market size decreases in the forest industry may be explained by new strengthened energy policies, emissions regulations and technological advancement (Hurmekoski & Hetemäki, 2013). One of the bright examples of such may be school notebooks, which are no longer used in the same quantity as 15 to 20 years ago.

Finland is famous for its forests as a result forestry and wood processing industries play a significant role in the country's economy. Nowadays such wood processing materials as lumber, paper, cardboard, packaging materials and pulp are the most produced and exported ones (Lipiäinen & Vakkilainen, 2021). Biodiesel and oils are created from the waste left over after the processing of wood (Lipiäinen & Vakkilainen, 2021). Additionally, there have been plenty of innovations in the wood industry, focused on the development of solutions in pharmaceuticals, adhesives, development of new materials that contain wood fibres and textile materials. Hence, wooden furniture and interior design are highly valued in Finland. Therefore, the most interest in interior design and construction lies in the development or production of wood materials, that would satisfy regulations for interior materials – such as fire safety, durability, toxicity, etc. Moreover, due to its acoustic and insulating capabilities, wood is preferable to other materials used for the interior.

2.1.2 Industry energy profile

Forestry is one of the biggest energy-consuming industries along with manufacturing, food and agriculture (Eurostat, 2022). According to statistics (Eurostat, 2022), in 2020 forestry is responsible for 21% of total energy consumption in Europe. On another hand, beside wood manufacturing, forestry industry includes production (harvesting) of the wood used for heating purposes. Based on the estimates given by the Natural Resources Institute Finland (Luke, 2022), 9.4 million cubic meters of forest chips have been used in heat and electricity plants in 2021. In addition to the 5.8 million cubic meters of forest chips used for energy generation purposes and 3.6 million cubic meters used for heating, some of the wood chips have been used for houses and saunas. The use of wood as an energy source by households has been estimated at 21,6% (13 154 GWh) in 2020. (Official Statistics of Finland (OSF), 2020)

2.1.3 Wood processing

In order to turn raw materials into products, the wood undergoes a great variety of machining and manual processes. According to EU Economic Activity Classification (or statista) (Statista, 2022): "*The production processes include sawing, planning, shaping, laminating, and assembling of wood products starting from logs that are cut into bolts, or lumber that may then be cut further, or shaped by lathes or other shaping tools.*" Further, the main wood processing steps applicable for this study are described. Among the rest of the processes, surface finishing processes such as grinding, and lacquering are included.

Drilling

Drilling is one of the most frequent procedures in wood product manufacturing. It is one of the factors that may affect the acoustic, adhesive, and durability processes. The energy consumed for the drilling, as well as other processes, is dependent on the moistness of the wood, its type, hard and softening points of the lumber. Application of the correct drill bits for the selected type of wood may allow a reduction of the energy consumed for the process.("Manufacturing Processes Reference Guide," 1994)

Milling

The milling process in manufacturing is concerned with the processing of the material (wood in this particular case) e.g., shaping, cutting, or grinding it by milling machine. The cutting surface of the milling machine resembles a rotating disk with several edges or "teeth". There is a great variety of materials and edge shapes for the cutter, which affect the efficiency of the process as well as the energy consumed during it. A correct choice of cutter for the specific material may simplify the finishing of the surface stage (grinding) or even eliminate it. ("Manufacturing Processes Reference Guide," 1994)

Turning

Another machining process – turning. One of the most used machines for the turning process is a lathe machine. In contrast to a milling machine, the material is rotated while the cutting tool is pressed against it to change the shape of the piece and or its diameter. ("Manufacturing Processes Reference Guide," 1994);(Özel & Karpat, 2005)

Grinding

Grinding is a machining surface finishing process. Depending on the requirement in tol-erances to the surface finish a great variety of techniques and abrasives are applied. In a CNC (computerized numerical control) grinding machine, the polishing and refining of the surface are done with the help of grinding wheels. (Hacksteiner et al., 2018)

Sawing

Sawing process is used for the division of material into several parts or for cutting un-necessary/ excessive parts off. The process can be done with the saw or CNC sawing machine. ("Manufacturing Processes Reference Guide," 1994)

Laminating

The wood laminating process is aimed at enhancement of the appearance of a wood piece as well as improving its durability. In this process, a thin layer of veneer mate-rial is glued or attached by other means to the main piece surface. The process can be done manually or with a help of machinery. While the manual process involves minimal use of electricity, in terms of production it is not always feasible. (Gibson et al., 2010)

Moulding

In order to achieve the necessary form of a material it can be moulded with the use of heat and pressure. Usually, the moulding process underlines the use of liquids or pliable materials, which are poured into a mould. Pliable materials however are pressed into the mould in order to achieve a desirable shape. (Umer et al., 2007)

Lacquer finishing or painting

Usually, lacquering is one of the last steps in the production of wood pieces, which depending on the final purpose of the piece can be either done before or after the assembly. In terms of energy consumption, it is highly dependable on the choice of the method, e.g., manual or machine. Additionally, the choice of method depends on the type of lacquer (air dry or UV cured). In the lacquer finishing process liquid layer of lacquer is sprayed or coated on the main side of the piece, which then is dried by either curing under the UV/Led lamps or through the evaporation of the solvent in the lacquer (Bekhta et al., 2018).

2.1.4 Appliance classification

Machining processes conduct higher energy consumption and therefore are the most looked into in terms of energy optimisation. Next, the description of appliance classification is given.

In order to produce a careful analysis of the energy efficiency of the company it is important to identify which of the appliance and devices are the most consuming ones. The classification of appliances is divided into four categories based on their operational states (Hart, 1992). The categories are a) on/off, b) Finite State Machines, c) permanent consumers and d) continuous variable devices.

- On/off

According to Hart (1992), these are the devices and appliances that generally have two states of operation – "on" – where the energy is consumed and "off" energy is not consumed. An example of such appliance on the factory floor could be – lighting. However, in the overall energy consumption of the enterprise, such appliances as simple coffee machines, kettles, lamps, etc. Although, appliances with greater complexity and "multiple discrete operation states" are excluded from this category.

- Finite state machines (FSM)

Based on the name of the category it includes devices that has more complex than on/off operation states but has a certain number of operations. The energy consumption can vary depending on the operation state it is on. Some of FSM devices has inbuild energy saving mode. (Hart, 1992)

- Continuous variable device (CVD)

This category includes the majority of the machines on the shop floor, which have a high variation of energy consumption rates, therefore this category of devices carries the biggest power load in manufacturing. The complication of the determination of specific operations electricity consumption is correlated with the *"continuous range of power draw and have neither repeated cycle for state transitions nor specific step-change features"* (Hart, 1992)

- Permanent consuming

Permanent consuming devices are the ones that have only one operational state. An example of such appliances is the fire alarm or smoke detectors. Despite the fact that the majority of permanent consuming devices are carrying a significant load of constant energy consumption in a ratio to their size and performance it is not always possible to update those for more flexible solutions or remove completely. (Hart, 1992)

2.2 Energy optimisation

2.2.1 Energy management

The industrial sector is responsible for 30% of total carbon emissions since it is one of the largest energy consumers. Additionally, the need for new solutions and reduction of energy consumption by the production has been caused by the growth of the energy prices as well as reenforced energy efficiency directives (Hasan & Trianni, 2020) . EED 2018, goals for 2030 are (European Comission, 2022): at least 32,5%, meaning *“In absolute terms, this means that EU energy consumption should be no more than 1128 Mtoe (million tonnes of equivalent) of primary energy and/or no more than 846 Mtoe of final energy (following the withdrawal of the UK)”*. In such circumstances (Nabitz & Hirzel, 2019), energy efficiency becomes essential in terms of ensuring security of supply, increasing cost efficiency, competitiveness and customers’ trust. (European Comission, 2022)

Energy efficiency (Abbassi et al., 2015) may be described as the proportion of energy utilized to accomplish a certain level of performance. The performance can be measured through revenue or profits gained from the goods, services or energy. The efficient use of the energy in the manufacturing is essential as it affects the overall environmental sustainability of the enterprise as well as reduction of production cost. Yet, another aspect of energy efficiency is enabling of the higher operations quality.

Higher energy efficiency may be achieved by means of effective energy management. According to (Qamar et al., 2021) planning, monitoring, and managing energy-related operations with the goal of conserving energy resources, reducing energy costs, and protecting the environment are all part of energy management. Similarly, according to the B.L. Capehart (2020), Energy management refers to the efficient and effective use of energy in order to maximize revenues and “increasing reasonable positions”(Hasan & Trianni, 2020). Energy management includes measuring and monitoring of the consumptions, collection and systematisation of the data, processing of the energy bill data, planning and purchasing (Abbassi et al., 2015). The use of LEAN principles in energy management, such as continuous improvement, plays a key role in the enterprise's efficient energy consumption. LEAN 6-Sigma strategy for the energy management concept is inspired from TQM (total quality management), which places a strong emphasis on reducing waste and enhancing customer satisfaction. Another supporter of this notion is the concept of continuous improvement. One of the methods applied to reduce lead times in the LEAN production thinking is the Value Stream Mapping. The extension of the VSM has been discussed by (Verma & Sharma, 2016) and (Müller et al., 2014a), it has been suggested that the VSM model is not fully inclusive and does not allow to evaluate energy usage withing production. Energy value stream mapping method will be discussed more closely in subchapter 2.3.1.

2.2.2 ISO 50001 Energy Management System

Due to the urgent need to save energy and cut greenhouse gas emissions worldwide, energy management is currently receiving significant attention on a global scale. Despite the fact that the energy consumption questions are not the least important for businesses profit-wise, the actual push towards application of the standards and energy saving practices comes from the governments.

ISO 50001 Energy Management System (EnMS) standard, which was released on June 15, 2011, contains a set of globally accredited energy management framework (iso.org, 2018) for businesses, which enable enhancement of energy efficiency, costs reduction and overall carbon footprint enhancement, thought the application of suggested technical and management solutions. Adhering to ISO 50001 EnMS standard may be beneficial for businesses also in terms of development of corporate culture of thoughtful energy and asset use as well as greater customer loyalty. (iso.org, 2018)

ISO 50001 Energy Management System standard – PDCA cycle provides businesses with framework for the optimisation of the EnMS (Energy management systems). Additionally, the “cycle” underlines the continuous improvement of EnMS, rather than single application of the standards’ requirements. The cycle consists of Plan, Do, Check, Act steps.

The first step “***Plan***” considers current state of the energy management systems in the enterprise, their correspondence with the requirements and possibility of updates. Next, the document with new or updated energy regulations is formed. Furthermore, the document should provide directions for implementing the new policies as well as the benefits to the business. This step is often managed by top level management. During the planning please it is crucial that the energy policy is communicated to the employees and key metrics for the energy performance tracking are provided.

Next step is “***Do***”, there the defined policies are implemented, if necessary, the stuff is trained. The communication and ensuring the awareness spread are crucial in successful implementation of new regulations.

“***Check***” step includes tracking and analysing updates from the perspective of internal policies, customer needs, as well as compliance with government regulations. Verification that the energy management system is operating effectively and producing the desired outcomes is usually done by internal audition.

The last step of the PDCA cycle is “***Act***”. In this stage, the implemented EnMS is reviewed and evaluated once again, considering the feedback from the internal audit. Based on the re-evaluation, optimizing procedures may be proposed. Finally, new plans or goals are made for the enterprise to achieve in terms of energy efficiency.

ISO 50001 can be applied as independent framework or in combination with ISO 140001, that is rather focused on the solely environmental issues and ISO 9001 – Quality Management Systems. These ISO standards follow same implementation structure and therefore - integrable.

2.2.3 Energy efficiency in MPS – manufacturing and production systems

Benali et al., (2007) notes, that one of the struggles met by the manufacturing and production systems lies in strive to balance minimal environmental impact, economic justification or feasibility of production, and energy efficiency concerns. As it could be seen from Figure 3 in order to find the solution, every of the aspects needs to be compromised to a certain level. (Abbassi et al., 2015)

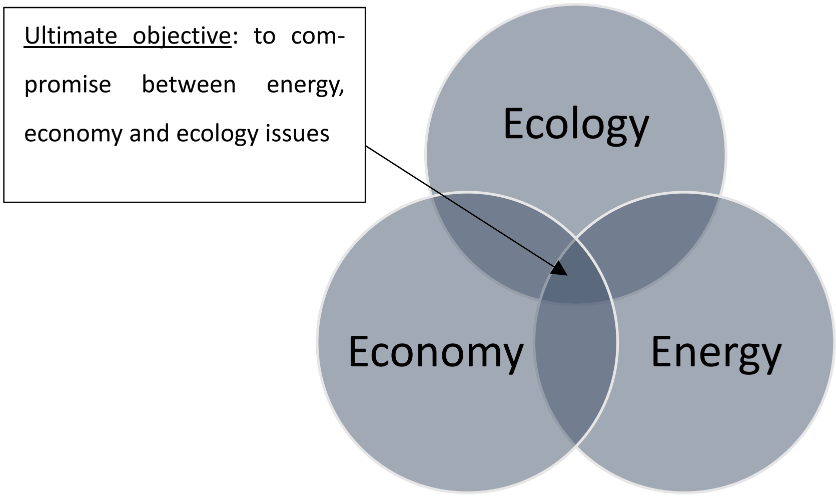


Figure 3 Conceptual basics of an optimization approach in industrial systems (Benali et al., 2007)

Manufacturing and production systems from the perspective of energy consumption divided into the energy input (energy required for the process) and output in a form of waste. One of the waste types is the lost heat (Abbassi et al., 2015). Therefore, minimisation of the lost heat may affect the efficiency not only in buildings, but also for the production as whole.

According to the Abbassi et al., (2015), energy efficiency optimisation can be done on the different levels: System, Process, Facility, and Equipment levels. Other studies (Diaz C. & Ocampo-Martinez, 2019; Micieta et al., 2016; J. Wang et al., 2019) propose optimisation of the management, technological and regulatory levels. Optimization on the management level focuses on the development of the strategies and frameworks for the achievement of the energy goals. The regulatory level, similarly, focuses on compliance to the standards and globally accepted frameworks for the energy efficiency of industries. Last, use of new technologies (new equipment, lighting, IoT) may positively effect overall energy consumption.

Operational scheduling may be seen as one of the approaches to energy efficiency optimisation of an enterprise (Nouiri et al., 2020; Yan et al., 2016). Scheduling is a process that defines the order in which operations are performed, taking into consideration the duration needed for the completion of operations (Zhang et al., 2016). This comprises completing given processes or tasks using the appropriate machinery and workers resources (H. Wang et al., 2018). Similarly, to the operations scheduling, a change in the route of production may be seen as beneficial in energy consumption. Routing of production refers to the documented process of scheduling the production of an item as outlines the sequence of operations required to produce a final good. It outlines where and how each activity should be accomplished as well as the order in which those activities must be completed (Manouchehri et al., 2020). The routing finds the optimal sequence of activities in order to manufacture the finished product at the lowest cost and in the shortest period of time (Manouchehri et al., 2020). The alteration of both operation scheduling and machine routing with the consideration of the energy consumption factor would be beneficial for cost reduction of production. Additionally, cautious resource allocation positively affects the environment (lower CO_2 emissions). (Diaz C. & Ocampo-Martinez, 2019);(S. Wang et al., 2015);(Yan et al., 2016)

2.3 Energy data analytics for production systems

Data analysis is related to a process of the collection of the data, its visualization, systematisation and monitoring that is then applied by the companies in the decision-making process. Data analytics is frequently associated with Business Intelligence, which includes process evaluations and pattern identification. Businesses may use such patterns to anticipate future trends and establish a business strategy (Muntean et al., 2021). Similarly, energy data analysis is a data mining method targeted at estimating an enterprise's energy efficiency and aiding in energy consumption optimization. (Xu et al., 2020)

2.3.1 Energy Value Stream Mapping

The original technique – Value Stream Mapping (VSM) applicable to the real working context has been introduced by Rother and Shook in 1999 (Khaswala & Irani, 2001). The main adjective of this conceptual idea was to reduce waste or non-value adding activities, and time used for the inventory as well examine the work-cycle periods independently from those “wastes”. Schillig et al., (2015) argues that the waste and working cycle cannot be looked at separately, noting that the working cycle itself contains non-value adding time in it and therefore should be accounted for. The extension of the VSM to include the energy aspects is concerned with the focus on non-value-added work already from the energy efficiency perspective.

Energy value stream mapping unlike VSM does not concentrate on the immediate value adding by the process, rather than on the visualisation of the energy used at each step of the work cycle. Integration of the energy aspects into the VSM enables the calculation and estimation of the amount of energy used and wasted in each phase of the work cycle. Therefore, it opens the potential optimization of consumption. (Verma & Sharma, 2016)

Some of the energy wastes are concerned with production and in particularly machining processes could be following (Verma & Sharma, 2016):

- Part placement, loading on and off
- Alignment
- Tool changing
- Idling
- Machine warming up, cooling down processes

Verma et al., (2021) propose that in order to achieve higher sustainability in MPS, integration of LEAN and six sigma is crucial and suggest extension of the EVMS to the LESSVSM – lean energy six sigma value stream mapping. The extension is supposed to be beneficial in terms of “rework and rejection,” enabling the minimisation of energy consumption.

2.4 Digital Twin

In the CIRP Encyclopaedia of Production Engineering (2020);(Stark, R., Damerau, T., 2019). A digital twin is explained as a virtual representation of a physical object that traces the changes in behaviours of the system through facilitating the information flow between the model and the twin. In other words, a digital twin is a digital copy of an object or process, which with a help of different sensors allow simultaneous tracking of the performance. Additionally, Qi et al., (2021) suggest that the Digital Twin entails building a digital representation of a physical object in order to imitate object behaviours, track the current situation, recognition internal and external issues, detect anomalies, reflect system performance, and forecast future trends. (Qi et al., 2021) Grieves described digital twin concept as a data cycle, which consists of three parts – a physical item, a virtual model and the information processing hub that links the real-world object and its virtual model. Grieves viewed this new concept as a viable base for PLM as well as a new approach to product manufacturing to satisfy targeted design parameters.

According to Grieves (Grieves, 2014), Digital Twin model consist of three dimensions:

1) Physical products in Real Space
2) Virtual products in Virtual Space
3) The data and information flow that enables communication between virtual and real products

Pang et al. (2021), described physical products in Real World or physical environment as a foundation for the building of Digital Twin. The physical object, despite the common understanding, does not only include the object itself, but also the environment.(Pang et al., 2021) This way, for example, a simulation of a shopfloor is not going to be complete without human interaction with the object. Some of the studies, contrary suggest that the physical product solely refers to the object itself. (Stark et al., 2017) (Grieves, 2014)

The next dimension is the virtual products in Virtual Space. The virtual space or virtual reality sometimes also referred to as a “virtual environment” are the interconvertible terms used to define the computer-simulated environment (Burgess & King, 2001), in which one can experience similar to real or a reality that is radically different from the actual one (Grieves, 2014). The virtual reality is perceived through a head-set gear googles.

In 1994 Paul Milgram and Fumio Kishino, in "A taxonomy of mixed reality visual displays" introduced the concept of a virtuality continuum (Milgram & Kishino, 1994). This concept defines "mixed reality" as everything between the real environment and the virtual environment (Milgram & Kishino, 1994). This mixture, or an overlapping information over the real environment could be called Augmented Reality (AR).(Muñoz-Saavedra et al., 2020) Similar to VR in order to experience AR simulations a perceiver requires gear, such as goggles or a smartphone with a camera. Although Augmented Reality has great potential in the DT targeted at the training of staff for dangerous works, over past few years it has grown the popularity in social networks.

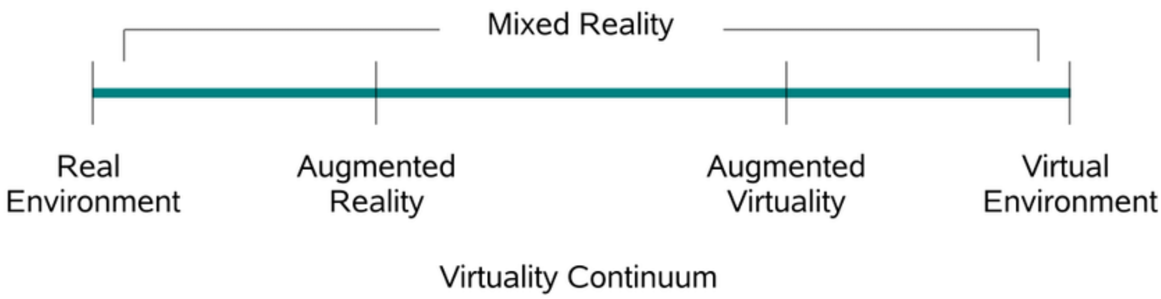


Figure 4 Reality-Virtuality continuum retrieved from: (Milgram & Kishino, 1994)

The virtual environment dimension is based on the model of the physical entity. The model can be developed through several methods: a) laser scanning, b) photogrammetry, 3) CAD modelling, which further is processed to create stationary or active digital representation. However, it requires to correspond to the rules of the real world – laws of physics, human interaction, etc. (Pang et al., 2021)

The third, according to Grieves (2014), is the information dimension. The third dimension is responsible for the information, collected from a real environment, and integration in the virtual environment. Such information is the data from the sensors, repositories, etc. For instance, the sensors attached to the machinery are tracking actual use time, which is then visible in the virtual model. This way, the actual energy consumption by the specific machines can be determined. Alternatively, the new data is brought into the simulation and tested prior to the integration into an actual layout.

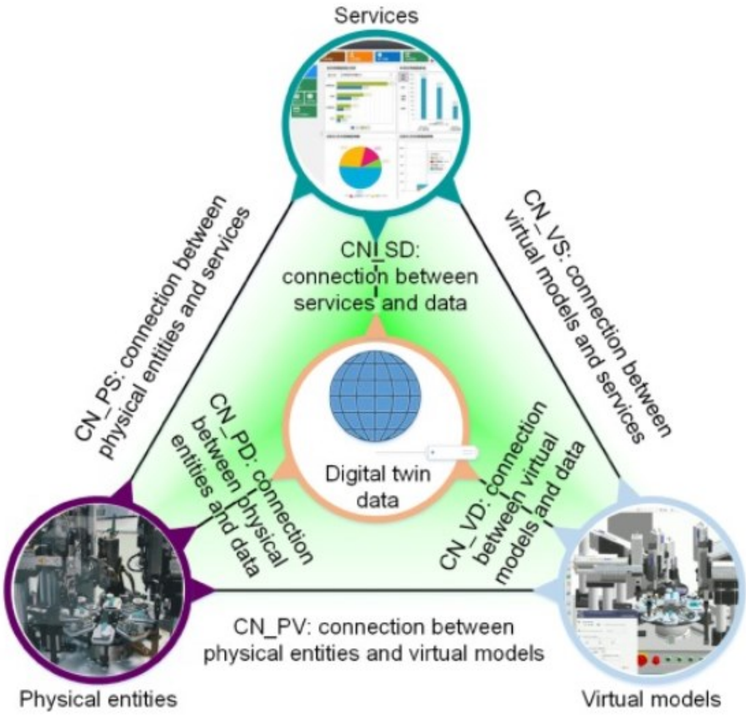


Figure 5 Five-dimension DT framework (source: Tao et al., (2019))

In the work « **Five-dimension digital twin model and its ten applications** » (Tao et al., 2019) suggested the 5-dimensional DT model, Figure 5 which consist already of: physical entities, virtual models, data, services and the connections. The addition to the previous model, proposed by the Grieves is in the defined services and connections as separate dimensions. This update enables deeper understanding of the DT concept and its applicability onto different spheres. Therefore, the DT would not be limited only to production (PLM) or air- and spacecraft. (Tao et al., 2019)

The service dimension is responsible for the user experience, ensuring all the soft- and hardware works properly though updates as well as the rest of the services, which fall under the XaaS (everything as a service) concept. The links in the new architecture can be thought of as transfer points that allow data to reach each dimension and allow the other four dimensions to communicate with each other without incidents. (Tao et al., 2019)

2.4.1 Digital twin application

The area of the application of digital twins is rather versatile. DT can be a single machine, e.g., plane representation or a system (a factory, power plant, smart home). The main purpose of the DT is to enhance performance of the object. Figure 6 shows the general application of the DT by the sector.

Alternatively, the same framework can be applied for the solution of problems that are not directly addressed. This research aims to propose a method for reducing and optimizing power usage by modelling the shop floor and assessing the machinery utilisation rates with varying loads. Further, other applications of the DTs are discussed.

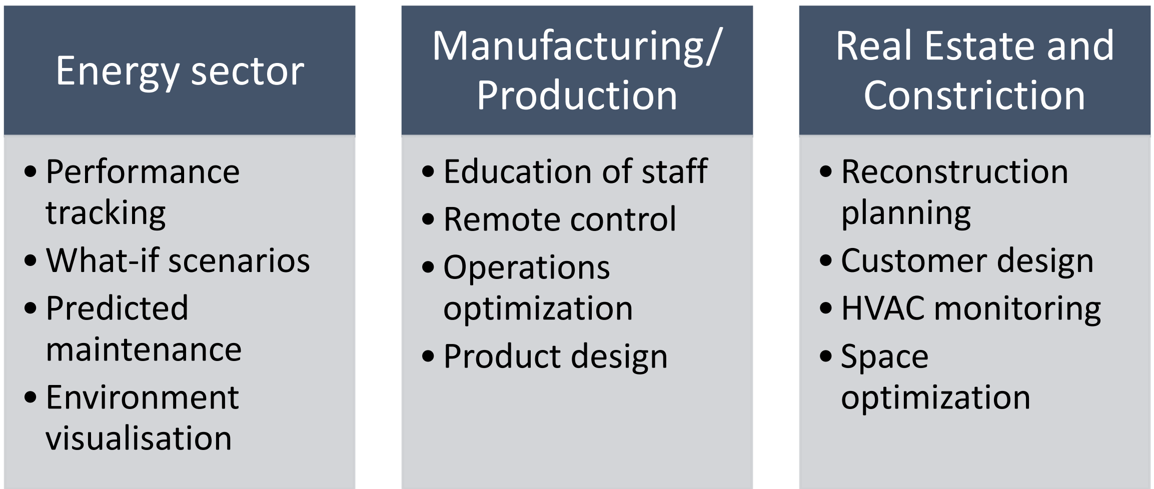


Figure 6 Application of digital twins by sector

1) Manufacturing digital twin

In manufacturing digital twins are utilized for the remote control of the operations, PLC, and planning for change, for instance. One of the most appealing applications of DT in manufacturing is the staff training for hazardous jobs in the virtual or augmented environment before completing comparable tasks in the physical environment. Among other utilization of DT, there is the predictable maintenance of the machinery and production capacity planning according to that. (He & Bai, 2021)

2) Real-estate and construction

The application of DT in construction and particular architecture comes from the renovation of historical buildings. Issues are lying in the necessity to preserve the original state of the building with all the historical accuracies. The development of the DT enables higher accuracy of the reconstruction and consequently the final state. Another utilization lies in the enhancement of the customer experience through VR or AR environment immersion.(Rafsanjani & Nabizadeh, 2021)

3) Digital twin for educational purposes

One of the applications of DT in education lies in unlocking new environments for the student, accessible from any location. The experience gained in VR through practical training or tasks similar to the ones conducted in the real environment enables a deeper understanding of the subject and greater confidence in the completion of such tasks in a real environment. According to Sepasgozar (2020), VR module integration in digital education has helped tackle the gaps in practical aspects. Additionally, VR training had a positive effect on reducing resource usage, while keeping the same level of quality of gained knowledge.

4) Human/ avatar creation

An avatar can be created by the laser scanning of a human. The main use of the avatar or digital replica of a human lies in the gaming industry, VR/AR training and education, and cinematography. The process of avatar creation is complicated by the fact that humans cannot stay still over a period of time it takes to scan the entire body. Nevertheless, the scan is then processed into a model that further can be animated. Despite that, nowadays avatars used in smartphone apps can be relatively easily created with a phone camera. One of the possible applications of avatars lies in the enhanced customer experience and business advertisement.

5) Energy digital twin

Energy DT is usually concerned with the modelling of the physical and operational characteristics of a power plant or other utility facility. One of DT use is to test for what-if scenarios even prior to construction. Yet another application can be seen in the improvement of operations and maintenance during the lifetime of a genuine facility, thus the completion of preventive maintenance. Alternatively, energy DT can be applied in order to tackle energy consumption issues for manufacturing and production systems, as well as any enterprise. (Borowski, 2021)

2.4.2 Techniques used to develop models

Next, there described main approaches used to develop virtual models. Among such techniques are laser scanning, photogrammetry, multi-method laser scanning + CAD model and modelling of the process through simulation software. Use of several model creation methods might allow achieving higher quality of the result.

2.4.2.1 laser scanning

LiDAR (Light Detection and Ranging) Scanning method is a technique that employs light to determine the distance between an item and its surroundings creating a point cloud in a 3d environment (Liang et al., 2016). The created point cloud can consist of multiple millions of points or more, depending on the size of the object. In order to develop a model from a point cloud, the data is processed and turned into mesh by either "*Delaunay triangulation or marching cubes*". One of the major advantages of LiDAR scanning lies in the high accuracy and speed of the data capturing. (Liang et al., 2016)

2.4.2.2 photogrammetry

Photogrammetry is usually described as the art and science of obtaining measurements from images. Alternatively, the photogrammetry method could be explained as the creation of a 3d model by the means of the extraction of the data from a large amount of pictures. In order to achieve the best digital copy of an object, the object needs to be photographed from a variety of angles with a certain degree of overlapping. (J. Chen et al., 2016; Shan et al., 2020)

Software tools analyse data with specifics of the camera and used lens to compare similarities from pictures and then position them in 3D space accordingly forming a model. The depth and textures may be applied to the meshed model. Photogrammetry can be used to establish geometries, positions, and orientations, as well as to track motions and deformations. (Ortiz-Sanz et al., 2021)

2.4.2.3 laser scanning + CAD

Next technique is the combination of the scan of a physical object or environment with the objects created in CAD software. The process consists of three steps: 1. Scanning or data capturing, 2. Point cloud processing, triangulation and mesh development, 3. Development of CAD model based on the physical environment geometry. (Giannelis et al., 2017) This method is usually applied for the development of architectural prototypes and reverse engineering in manufacturing, although Giannelis et al. (2017) notes that the latter one still requires further development.

2.4.2.4 Modelling

Modelling is usually done utilizing the simulation software, where the real entity – such as, for instance, the factory floor is replicated including all the main processes. The model then can be adopted for the change, used for production/ storage planning, etc. One of the main benefits of the modelling to the rest of the methods used to create virtual entities is it's the time consumed on the reconstruction of processes as well as the ability to interact and visualise change immediately.

2.5 Simulation of production systems

A common approach for designing and analysing production processes is simulation. The basic idea behind it is to simulate real-world systems with utilization of models of the machinery, tools, human resources, etc. in order to understand how they behave over time (Rödger et al., 2021). One of the most commonly used simulation types – is discrete event simulation (DES) (Negahban & Smith, 2014). Geoffrey Gordon has developed the concept of discrete even simulation along with the General-Purpose Simulation System concept in 1960 (Barbosa & Azevedo, 2017). DES could be defined as an approach for simulating physical environment systems that may be divided into a number of conceptually separate processes that progress separately throughout time. Since there is no presumption that the system will change between two sequential events, current simulation can move forward to the following simulation event. Each event is assigned required amount of time and occurs according to a predetermined process order. (Barbosa & Azevedo, 2017)

Simulation of production of manufacturing systems carries wide variety of benefits for the company. Application of discrete event simulation (DES) may be used as a tool for evaluating production change. DES enables conduction of the research and tests, what-if scenarios and plan preventative measures, enhance product as well as processes at all of the stages, operations without interfering with an ongoing production system. Additionally, simulation of production systems enables companies to evaluate current layout or to plan future one, throughput times, material handling, resource allocation, and supply chains. Moreover, to assess improvement ideas before putting them into practice in a real context. (Flores-Garcia et al., 2016).

Other types of the most commonly used simulations in MPS and their application areas are SD (System dynamics), ABS (Agent-Based simulation), Monte Carlo (MCS) and Petri net (Jahangirian et al., 2010). SD or System Dynamics simulation has been formulated by J. Forrester in 1950 as a “Industrial Dynamics”. SD is a continuous simulation method, where complex nonlinear systems are accessed through utilization of feedback loops, flows and stocks (Barbosa & Azevedo, 2017). Unlike rest of mentioned above simulations, it is focuses on the global causal dependencies (Gejo-García et al., 2022) and policies rather that a single incident or a factor that may affect the system. Nevertheless, time factor as well as delays plays crucial role in such systems, therefore it has been originally for SCM (supply chain management). Additionally, SD enables analysis of strategies, forecasting, simulations across long periods of time and testing how the behaviour of whole system would change in a response to certain events. The ABS enables assessment of the production system through the “agent” impact definition on the system. The “agent” in such simulation can be human, devices, machinery that carry a certain behaviour and can affect the behaviour of the rest of the system. The most application of the ABS may be seen in the business areas and does require sufficient amount of data on the “agents” behaviour (Barbosa & Azevedo, 2017) . Next simulation type is the Monte Carlo (MCS) method. MCS is generated from empirical data of actual production or manufacturing system records. MCS is concerned with the analysation of risks for business. The last simulation type in the table is petri-net simulation. Petri net can be thought as a simple version of DES that is commonly utilized in MPS simulation (David & Alla, 2010; Grobelna & Karatkevich, 2021).

Simulation type	Application area	Software, tools applicable	Reference
DES – discrete event simulation	SCM, QM, Scheduling, WHM, MHM, Resource allocation, JIS	AnyLogic, Enterprise dynamic, Siemens Plant simulation, SIMUL8, Visual Components	(Negahban & Smith, 2014)
SD – system dynamics	SCM, forecasting, QM	AnyLogic, Simantic SD, Simulink, GNU Octave	(Barbosa & Azevedo, 2017)
ABS – Agent-based modelling	Process engineering,	AnyLogic, NetLogo	(Barbosa & Azevedo, 2017)
Monte Carlo (MCS)	Risk management, Inventory management	iThink, GoldSim, Excel	(David & Alla, 2010; Grobelna & Karatkevich, 2021)
Petri net	Capacity planning, SCM, Process engineering	MATLAB, Simulink, SimLab simulation	(David & Alla, 2010; Grobelna & Karatkevich, 2021)

Table 1 Description of simulation types

Considerable number of the studies in simulation of production systems done with a major focus on the optimization of the design (Flores-Garcia et al., 2016; Negahban & Smith, 2014; Rödger et al., 2021), production line or even a single production process, lacking attention to their possible use in energy consumption optimisation.

2.6 Alternatives to the basic electricity or applicable solutions

This subchapter represents alternative solutions that may be applied in the company case in order to reduce energy consumption as well as remove part of the weight for the grid caused by the peak consumptions. Those solutions include solar energy, heat pumps, wind power, energy storage and capacitor batteries solution for the reduction of the reactive power in the machinery.

2.6.1 Solar power/energy

The amount of solar energy could satisfy energy needs of the planet, as it is exceeding both current and future demands. Solar energy is non-pollutive, quite predictable, but relatively expensive to harvest (Rahman, 2016). However, in comparison to the other renewable sources and fossil fuels, solar energy has grown in popularity among industries and domestic users.

Although solar energy (radiation) is one of the most powerful energy sources, its concentration significantly decreases on the planet's surface for it to be safe. More than half of the sun's rays are absorbed by the atmosphere and clouds. Infrared, ultraviolet, and electromagnetic radiation comprise the remaining half of the rays.(Kabir et al., 2018; Sampaio & González, 2017)

Solar energy can be utilized or collected mainly through photovoltaics (e.g., solar panels), solar heat ovens (concentrated solar power) and use of solar energy for heating and cooling purposes. The application of photovoltaics on a small scale can be seen in old calculators, garden lighting as well as on a larger scale – households and, for instance, production. Photovoltaics is concerned with the process of the sun rays or sunlight conversion into electricity within a PV cell. (Rahman, 2016) In other words, PV cell transforms sunlight into energy by means of PV effect. Energy is produced, when sunlight contacts junction, that can either consist of metal material and silicon (semiconductor), or two semiconductors (p-n junction). In p-n junction, p-type silicon is positively charged with spacings, and n- type, has excess of electrons and is negatively charged – enabling electrons to transfer between p and n sides, forming an electric field. (Sampaio & González, 2017)

One PV cell generates about 0.46 volts of electricity; however, a solar panel may consist of many PV cells, enabling production of 0.170 kWh- 0.35 kWh (average solar panel). Logically, increase of amount of PV cells will lead to the increase of harvested electricity. Yet, PV cells' efficiency is estimated as maximum of 20%. Majority of the solar panels are made with a use of crystalline silicon. (Rahman, 2016) proposed that change of the semiconductive material may positively effect efficiency of cells, resulting in its cost reduction. Nevertheless, despite many benefits, solar panels efficiency is very dependent on their location and weather conditions (Li, 2018).

2.6.2 Heat pump

Heat pumps are proven to be highly efficient in optimisation of electricity consumption (Z. Wang et al., 2021), while positively affecting the carbon emissions and enhancing overall "*efficiency of buildings*" (Le et al., 2020). According to the Z. Wang et al.,(2021) heat pump could be defined as a device that is operating through absorption of the heat (air, water, soil) on the cold side and then transfer it to the side with higher temperature - cooling it. The circulation of the heat in a heat pump is achieved by circulation of the refrigerant. A refrigerant is a liquid that evaporates through absorption of the heat from the environment, usually consisting of outside and internal heat exchangers. Next, in a heat exchanger, the evaporated refrigerant is compressed and by releasing the heat to environment – condensates. Such cycle is called – refrigeration cycle. (Z. Wang et al., 2021)

Hu et al., (2019) suggest that energy efficiency of heat pumps can be done via elimination or reduction of the heat waste as well as system optimisation. In a household use significant reduction of the basic electricity use can be achieved by combination of heat pump and solar panels (Z. Wang et al., 2021). Industrial application of such approach would enable to reduce the overall electricity consumption from the grid. High temperature heat pumps (HTHPs) may be applied for waste heat recovery purpose, however their integration into existing systems is quite complex and yet, not sufficiently researched (Arpagaus et al., 2018).

The most commonly used heat pumps are:

1. Air source heat pumps
2. Exhaust air heat pumps
3. Geothermal heat pumps

Air-Source Heat Pumps (ASHP)

Air source heat pumps are one of the most commonly used for heating and cooling purposes, and include air-to-air, air-to-water heat pumps. Wang et al.,(2021) notes that ASHP could substitute fossil fuel (e.g., coil) boilers in water and air heating as well as reducing carbon emission of district heating. Air source heat pumps function by generating energy from the air out of building (Carroll et al., 2020). The distinguish in air-to-air and air-to-water ASHP lies in the different heat dispersion systems. Air-to-water heat pumps distribute heat through "hydronic systems" – radiators, water floor heating, etc. In air-to-air heat pumps, heat is dispersed throughout the air conveying systems (ventilation, air ducts).

On the other side, negative aspects of the ASHP use lies in its high dependency on the external temperatures. Therefore, it is less suitable for the places located in a cold climate. Lower COP of heat pump can be explained by the decrease of amount of heat energy that can be obtained from external air during cold seasons. Another significant disadvantage of the ASHPs in a cold climate appears during temperatures below 0 Celsius and it prompts frost formation on the evaporator. Moreover, frost might trigger failure of the ASHP system, by disrupting the cycle of refrigerant flow. (Z. Wang et al., 2021)

Geothermal source heat pump (GSHP) and Hydrothermal source heat pump

Geothermal source heat pumps produce energy from ground (soil) or water heat. GSHPs can be used for both heating and cooling of the internal spaces (Chahartaghi et al., 2019). Typically, GSHP includes subterrain pipelines, refrigeration cycle and heat exchanger that is located on the surface. (Mao & Chen, 2017) Unlike ASHPs, ground source heat pump systems are less dependent on the weather conditions as ground temperature does not fluctuate drastically throughout the year and GSHP is able to deliver higher COPs. (Deng et al., 2019);(Corberán et al., 2018; Urchueguía et al., 2008).

Exhaust air heat pump (EAHP)

Exhaust air heat pump is concerned with air heat recovery. The heat is extracted from the air exhaust and used to heat water, flooring, and supply air. Due to the fact that EAHP uses exhaust air, which is estimated at around 21 degrees throughout the year, it is less reliant on weather conditions. However, the application of such solution had been seen to increase electricity consumption significantly due to insufficient heat recovery and need for additional heat sources.

A different angle on the problem is shown in the study done by (Psimopoulos et al., 2019) proposed new algorithms for heat pump controllers that allow reduction of electrical heating support. The majority of the studies (that support this claim) has been done for the residential houses' application of EAHP. (Pylsy & Kurnitski, 2021) According to the study completed by Fan et al., (2021) EAHP performance in Finnish and Nordic climate allow to save up to 31% costs for the heating. This study suggests that the implementation of EAHP should be as a supporter to other heating systems, rather than a sole solution.

Solar assisted heat pump (SAHP)

Solar assisted heat pump integrates both solar thermal panels and heat pump system. The idea behind SAHP is enhancing efficiency of both solutions through covering greater range of applications and reducing risks. Solar panels can be added to already existing heat pump system. This way COP (coefficient of performance) of solar assisted heat pump could be increased up to 30% in comparison to only heat pump solution (Z. Wang et al., 2021). According to the study completed by Fan et al., (2021) EAHP performance in colder climate may be less than expected. Coefficient of performance in temperatures lower than – 16 °C estimates approximately at 1.04 to 1.89 (Fan et al., 2021).

2.6.3 Wind energy

In past few years in Finland there has been notices growth of interest towards such renewable source as wind energy for the residential and commercial use. According to the statistics in previous year Finland has produced enough wind energy to provide 11.8% of its domestic needs, or 9.6% of the country's annual electricity demand. In comparison to 2019, production increased by 29% (FWPA, 2023). Wind energy is one of the renewable energy sources and in comparison, conducts one of the least environmental impacts, as it does not result in carbon pollution. Therefore, the location for the installation of the wind energy harvester can be chosen according to the most favourable conditions. (Saidur et al., 2011) It is often seen that wind farms are located in rural areas or close to farms. Despite the fact that the wind turbine produces noise pollution, according to Saidur et al., (2011) from a distance of 350 meters, the noise is lesser than the one produced by a refrigerator.

The energy from a wind power is usually generated by the wind turbine. There are two main types of wind turbines according to the axis – horizontal (HAWTs) and vertical ones (VAWTs). In horizontal wind turbines, rotary blades are moving parallel to the surface, while in a vertical one rotary blade move perpendicular to the surface. The wind turbine consists of rotary blades or propellers, a tower, a gearbox and a generator. The rotary blade of the wind turbine has similar to the helicopter propeller aerodynamic properties. The movement of the wind across the blade results in a decrease in the air pressure on one side. The energy is produced when the difference in the air pressure on the sides of the rotary blade results in the rotation of the propeller (Burton et al., 2011). In other words, the propeller rotation occurs when the lift force exceeds the drag force. The rotor is connected to the direct drive turbine generator, however, in other cases, a turbine is speeded up by the gearbox. It is possible to use a less powerful generator when a gearbox is used. Generally, the electricity is produced as a result of the conversion of aerodynamic force into generator rotation. (Burton et al., 2011)

According to the Betz law that has been published in 1919 (“Introduction to the Theory of Flow Machines,” 1966), the maximum energy that can be extracted with wind turbine or its efficiency is estimated at 59.3%. Practically, majority of the conventional wind turbines maximum operating efficiency reaches 75-80% of the Betz estimation (Burton et al., 2011). Economically this limitation affects feasibility of the wind turbine installation. However, increase of number of turbines in the wind farm compensates its efficiency limitation.

Installation of the wind turbine in the urban area is concerned with several risks. First of all, the location of the installation may become unsatisfactory over time as new and possibly higher than the level of installation buildings appears. In other words, surrounding constructions higher than the installation may prevail wind from the turbine, limiting its efficiency.

2.6.4 Energy Storage Systems

The growth of the application of renewable energy sources has created a need for reliable, durable, ecological, and feasible solutions to storing energy. It might be explained by a discrepancy between the energy generated by the renewable source and the demand for energy at the time. Energy Storage Systems or ESS enables balancing the production and utilization rate of the electricity (Amiryar & Pullen, 2017). While the energy is overproduced it can be stored in ESS, which then later can be applied according to needs. Chen et al. (2020), suggest that ESS enables peak shaving and load stabilizing by delivering idle energy to the system. Moreover, it may affect positively cost reduction by storing the energy from the grid at a minimal price and utilizing it when the price is high.

There are great number of energy storage systems, which could be generally divided into Mechanical energy storage (Flywheel or compressed air storages)(Amiryar & Pullen, 2017), Electrical or magnetic energy storages (e.g., capacitors), Chemical energy storages (SNG or synthetic natural gas), Thermal energy storages (Aktaş & Kirçiçek, 2021) and Electrochemical energy storages (Li-Ion batteries) (T. Chen et al., 2020).

The latter ones are known for their high flexibility and compatibility with the majority of energy systems. The principle of electrochemical energy storage work lies in the reverse oxidation-reduction reaction, which is used by batteries to turn the chemical energy present in its active components into electric energy. One of the most popular technologies in electrochemical energy storage systems is a Li-Ion batteries. Li-Ion battery consists of negative charged electrode (anode), positive charges electrode (cathode) and electrolyte. During the charging process, ions in electrolyte are migrating from cathode to anode. Usually, anode is made of lithiated graphite (LixC6), and cathode is typically made from metal oxide, for example lithium oxide (LiMn2O4, LiCoO2, LiFePO4) (T. Chen et al., 2020). The most commonly used electrolyte is comprised of lithium salt, such as $LiPF_6$ which is dissolved in organic carbonates.(Crawford et al., 2018)

Compared to other battery kinds, Li-Ion (Lithium-Ion) batteries perform better in terms of a prolonged life cycle, greater efficiency, temperature tolerance, and one of the highest energy densities. (T. Chen et al., 2020; Georgious et al., 2021) The application of Li-Ion batteries can be seen in Electrical Vehicles as in stationary use. The stationary use of Li-Ion batteries enables stabilization of the grid and therefore, carries a great interest in their applications. (Crawford et al., 2018) One of the disadvantages however is concerned with the price of the batteries and its feasibility for enterprise needs application. (Georgious et al., 2021)

2.6.5 Capacitor banks

A capacitor is a form of an ESS, namely an electrical or magnetic energy storage, where the magnetic or electrostatic fields are used to store energy (Georgious et al., 2021). A capacitor bank is a device that consists of multiple single (capacitor units) with comparable specifications capacitors that are connected in parallel or series for the purpose of gathering electricity. Stored energy is then may be applied to counteract or correct power factor lag or phase shift in the power supply (Nokian Capacitors, 2004). The main purpose of capacitor banks is to compensate the reactive power (of the machinery for instance on the grid) and to correct the voltage level through stored reactive power from the capacitor bank. (Nokian Capacitors Ltd., 2006)

Generally, capacitor banks can be divided into low and high voltage. Low voltage capacitor units may be connected into fixed or automatically controlled capacitor banks. The main difference between the fixed and automatically controlled lies in the ability to control the anticipated power factor through fuses and contactors in the latter ones. The fixed low voltage capacitor bank fuses are anticipated to satisfy the current 1.7 times of the rated one and connection cables withhold 1.43 times rated current. (Nokian Capacitors, 2004) High Voltage ones are more commonly seen in the industrial application. HV capacitor bank enable reactive energy congregation slightly under the required one for the operation of the machinery, thus reducing the spikes and grid overload. In addition to the reactive power compensation, such capacitors “increase the voltage and improve the power capacity of the line” cumulatively resulting in decrease of the energy consumption costs. (Nokian Capacitors, 2004);(Nokian Capacitors Ltd., 2006)

3 Methods

In this chapter methods used for the optimisation of the energy consumption study are represented. Methods are aimed at the analysation and systematisation of the knowledge gained throughout the research. One of the main goals of this study is to propose a solution for the specific case. This required a complex approach to the development of an energy value stream map, analysing the data set, and simulation of the shop floor.

Yet another of the goals of this work is to study the applicability of the simulation (early digital twin) for the purpose of the enhancement of the energy consumption of an enterprise. Therefore, it is important to identify tools that can be used. Production simulation tools applied in this study are Visual Components.

3.1 Energy data analysis

3.1.1 Data analysis

One of the adjectives of the data analysis is to be able to make judgements and predictions based on the numbers. Majorly, analytics is done with a help of software, however it may be done by pen and paper on a small scale. The steps that are typically taken when conducting the data analysis could be divided into:

1. Definition of the problem
2. Collection of the appropriate data for the analysis
3. Checking of the raw data for the correct format, errors, repetitions and absence prior to the conduction of the analysis.
4. Cleaning and sorting the data
5. Selection of the correct or suitable data processing method, depending on the final requirements and analysis
6. Results interpretation (visualization, clarification)

The first step is the definition of the problem to be solved by the analysis. During this step, the broad ideas about what and in what form results are needed should be clarified. Previous approaches to solving a similar problem could be examined and evaluated for the applicability in the current case. Next, the collection of the data for the analysis, which can be done through internal sources, open sources such as statistical databases, data collected for the sensors and interviews. Interviews in the quantitative analysis may play a filter role for the quantitative data as well as help in the selection of the method for the analysis. This is therefore followed by the cleaning of the raw data from errors, repetitions and irrelevances. One of the factors in the cleaning and sorting of the data step is the software that is going to be used for the analysis. Next, after the data for the processing is authenticated and accepted, the analysis method may be selected. (Broby, 2022). After the analysis is conducted, the results gained need to be interpreted and visualised. Data visualization can be done in graphic, histogram, or chart format and presented in a manner that is most helpful for solving the initially stated problem.

It is important to notice, that the selection of the tools for the analysis is highly dependent on the legislation and governance of the sensitive data. Sensitive data according to the European Commission (GDPR) (Truong et al., 2020), for instance, may include personal information that may disclose political views, ethnicity, religion; data related to the health of one being, etc.

3.1.2 Energy value stream mapping

Energy Value Stream Mapping is one of the methods to access energy consumption of an enterprise. It is used for better understanding of the processes impact in overall energy consumption on the shopfloor. EVSM (Energy Value Stream Mapping) is built upon the Value Stream Mapping concept (Verma & Sharma, 2016), therefore it can be used to determine the utilization of the energy of each process as well as energy waste (Mudgal et al., 2021). Based on the clear and visual understanding of a “current state” experts can plan for the “future state” and define steps to be done in order to achieve it. The EVSM in this case focuses on the machining processes of the production of the clattering material.

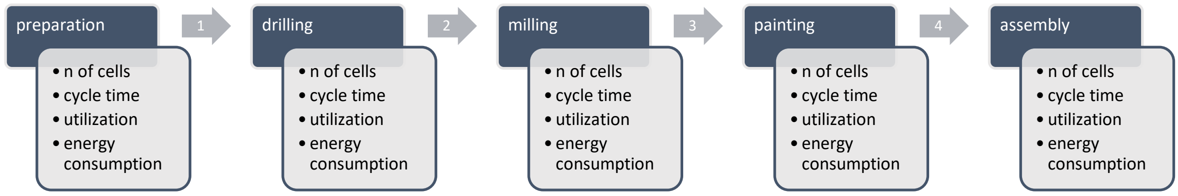


Figure 7 Production flow example without the supply chain activities

The identification of the processes (Figure 7) with the highest energy consumption is one of the main tasks in the assessment of the company energy profile along with analysis of the overall energy consumption data. It is possible to divide overall energy consumption of the manufacturing system by – a) process, b) machinery/ infrastructure and c) HVAC and lighting. (Rödger et al., 2021)

Processes include all of the steps in the production of an item and its electricity demand. The infrastructure and machinery consist not only of the demand for the specific machines included in the production of an item but also their maintenance, material use, further upcycle and replacement (e.g., robots, welding guns, installations for compressed air and centralized lubricant system) (Rödger et al., 2021). Heat, ventilation, air-conditioning and lighting are carrying significant energy consumption even though it is not directly used for the item production. Nevertheless, all the areas in an enterprise that are consuming heat, light and ventilation need to be considered for a more accurate assessment. However, this study concentrates on the analysis of the shopfloor energy profile and ways to improve it.

Assumption of the base electricity load may be done through calculation of the average energy consumption during the days of the year when there has been no production, e.g., – holidays, and weekends. The amount of base electricity utilisation is going to differ during warm and cold seasons. During summer and warm periods, it is possible to assume that the main load comes from the HVAC and lighting. During winter or cold periods – floor heating is added to the base load.

The definition of the energy consumptions of each of the processes could be divided into following steps:

1. Collection of the data on the machinery
2. Determination of the use of the machine throughout the day
3. Approximation of the consumption

Nevertheless, the complexity of the data collection process comes with the accuracy of the measurements and the availability of sensors or IoT systems. Following the steps above, first of all, the machinery with the highest consumption needs to be defined as a change in their operation that might affect the overall energy consumption profile significantly. Depending on the availability of the technology data can be either gathered with the help of sensors or manually. If none of the above-mentioned methods of data collection is possible, numbers may be approximated according to open-source databases. Next, the energy consumption profile of the machine is evaluated, and its actual use efficiency is determined.

3.2 Simulation of production – development of the model

There are plenty of production simulation types, however in this case Discrete Event Simulation (DES) has been used. DES enables testing of what-if scenarios as well as evaluation and comparison the efficiency of current with future layout. Therefore, planning for future changes can be done with a greater accuracy and certainty.

3.3 Software tools used

3.3.1 Visual components

Visual Components is a tool for simulation of the production. Along with the simulation of the production it is possible to see statistical returns from the created layout Figure 8. Changes in the layout or the routing of the production are visualised immediately. One of the advantages of the VC software is simulation for short period of time as well as longitudinal. It has a possibility to program robots, workers and machinery components as well as insert own data to simulate the process with the predefined numbers. The simulation type used in the Visual component's software is a DES or discrete event simulation. Therefore, it is possible to say that it makes it possible for businesses to assess their present layout or plan for future ones, throughput times, materials and resource allocation.

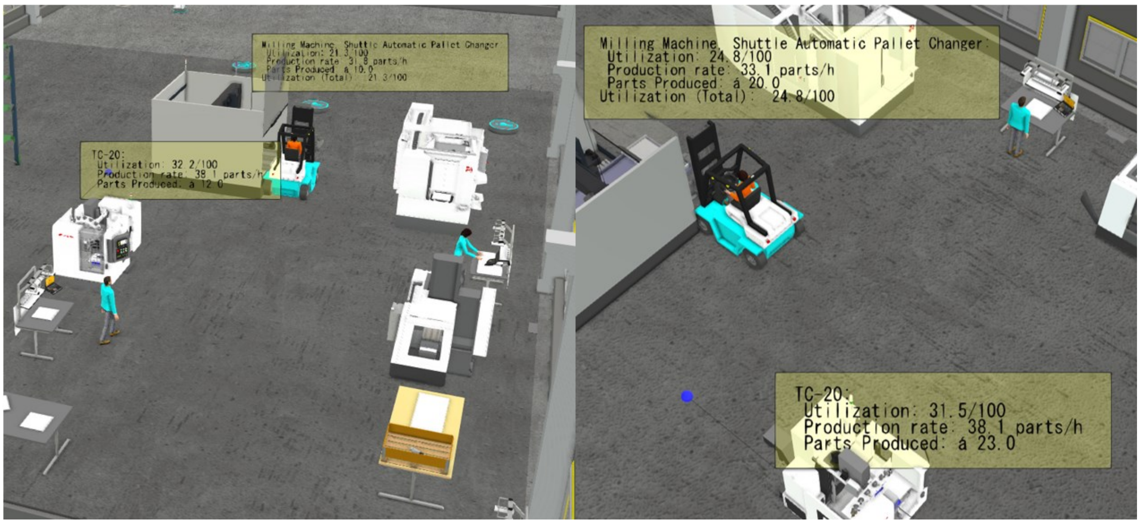


Figure 8 Visual components basic layout

3.4 Efficiency calculation of alternative solution

3.4.1 Coefficient of performance

Coefficient of performance of COP of a heat pump based on the amount of heat produced to the energy consumed by the pump. A typical COP of a ground source heat pump is around 4,5, therefore for the production of 4,5 kW units of heat the pump consumes 1 kWh of electricity input. The calculation of COP in the heat pump can be seen in the equation 1, where “Q” is the useful heat and “W” is the work put into the process.

Coefficient of performance:

$$COP = \frac{|Q|}{w} \tag{1}$$

4 Results

The study's findings are presented in this chapter. Results are divided into several parts, which are aiming to answer questions defined in the introduction chapter. The first part of the result chapter is focused on the description of the case company that consists of the historical background, production site description, machinery overview, solutions that have already been implemented presentation and evaluation. Additionally, necessary for the full understanding of the case energy contract specifics are given. The next section of chapter 4 is focused on the presentation of energy analysis results. Further, the process of creation of the model and results of production simulation are presented. Next, alternative solutions to the existing ones are proposed. Last, based on the research final solution is produced in subchapter 4.4.

4.1 Case company description

"With Puucomp's advanced surface solutions, you can bring the authentic feel of wood to public spaces - in a fire-safe way. You are free to come up with ideas - we will find a high-quality solution for you. Oy Puucomp Ab - Nordic manufacturer and pioneer of surface materials since 1987. We also implement solutions that have never been done before" Oy Puucomp Ab (Puucomp, 2022)

The case company, Puucomp, is one of the largest wooden surfaces (interior cladding panels) manufacturers in Finland. Puucomp cladding panes are considered to be exceptionally durable and fire safe. Among Puucomps' products are perforated acoustic panels (used in the auditoriums and concert halls), real wood veneer (a thin layer of the wood, that tops the shield from gypsum or plywood), providing technical solution, painted and laminated materials. The works can be seen in Aalto University – Toolo Campus, Supercell head office (Helsinki), etc. Figure 9 represents the Pasila railway station that is one of the largest in Finland, which appearance has been elevated with a help of lath elements from the Puucomp. (Puucomp, 2022)

Figure 9 Pasila station in Helsinki (Puucomp, 2022)

The acoustic panels are highly customizable; therefore, it is a combination of a machine and human process. Acoustic panels can be made either for the purpose of dampening the sound or diversion. The amount of perforations and their size depends on the purpose of the panel. The best sound is achieved by “nano perforation”; the typical size of the nano perforation hole is around 0,5 mm and are placed with a 1,75 to 2 mm distance from the centre of each hole. Unlike normal perforation in Puucomps panels, nano ones are applied for the either top layer of wood veneer or lamination. In order to enhance the interior different patterns may be applied. (Puucomp, 2022)

Fire safety is one of the raised questions when considering the wooden interior. There are several general standards applied to the building materials in EU. The classification of materials according to EN 13501-1 described as A1, A2, B, C, D, E, F with additional classes s for smoke production and d for droplets formation. Panels produced by Puucomp satisfying all the necessary requirements for the fire safety. The interior cladding panel, for instance, falls under the A2 (will contribute to the fire to an extremely limited extent) /s1 (the smoke production is limited) /d0 (no flaming droplets or particles occur) (Puucomp, 2022) class and can be used in the location with high necessity for the fire resistance. Additionally, panels are satisfying the M1 emission class, indicating that it is a low emission building material, it does not produce any toxic emissions and is completely safe to use in any spaces. (Puucomp, 2022)

4.1.1 Production site

The company is located in Kristiinankaupunki, the western part of Finland. It is important to understand the location as there are certain specifics in the weather conditions, which might affect overall energy consumption. Similarly, the weather conditions affect the feasibility of installation of one or another supportive renewable energy solutions to the mail source electricity from the grid. Generally, the location as well as the condition of the buildings of the company allow to consider wide range of solutions to implement in terms of energy optimisation. The shop floor consists of two buildings. The main building A is divided into several sections, according to the types of the works completed, following the production line. In the second building the final or finishing steps, such as painting, and lacquering are completed. Additionally, in the building B (Figure 11) some of the final products and machinery that is currently not in use are stored. From the perspective of the energy consumption, it is possible to see that highest energy is consumed within building A.

Figure 10 Building A layout (from: Visual Components software)

Description of production lines/shopfloor can be seen in the figures 10 and 11. As mentioned previously it consists of several buildings, A and B. Building A (Figure 10) is divided into 2 sections in between which there has been installed the automatic door with sensors in order to prevent heat loss, however that has resulted in an increase in electricity consumption.

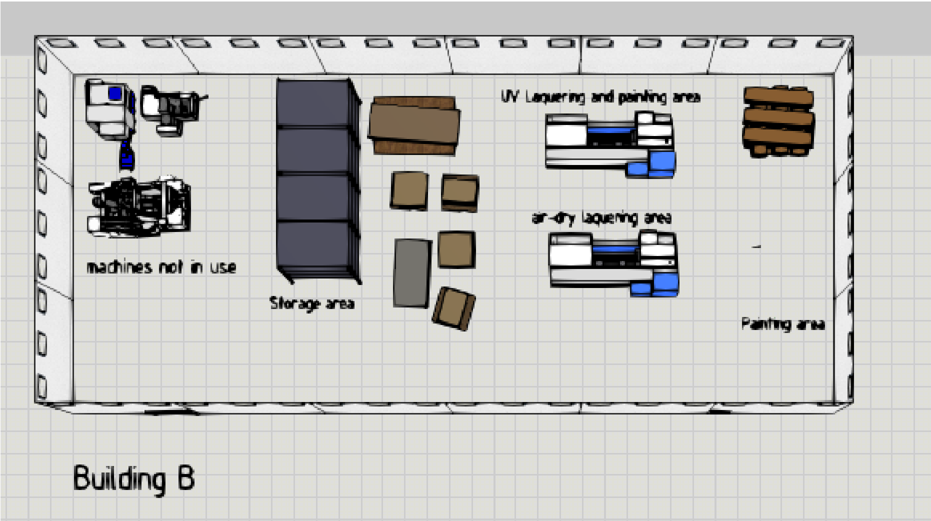


Figure 11 Building B layout (from: Visual Components software) (Puucomp, 2022)

The most energy consuming steps in the production of an interior cladding panel are the machining processes. Additionally, machining processes are the least flexible in terms of the WIP scheduling.

4.1.2 VR walkthrough the layout

One of the advantages of the simulation software used is the VR layout representation. The layout is interactive, and it is possible to see processes from inside. Virtual visualisation of the shopfloor gives more clarity of the processes. Additionally, the layout can be alternated in the VR view, therefore the space of the shop floor could be utilized with greater efficiency. The VR simulation can be previewed in several modes – the first view or 1:1 scale (Figure 13), the model is realistically scaled for the viewer and preview “on the table” (Figure 12).

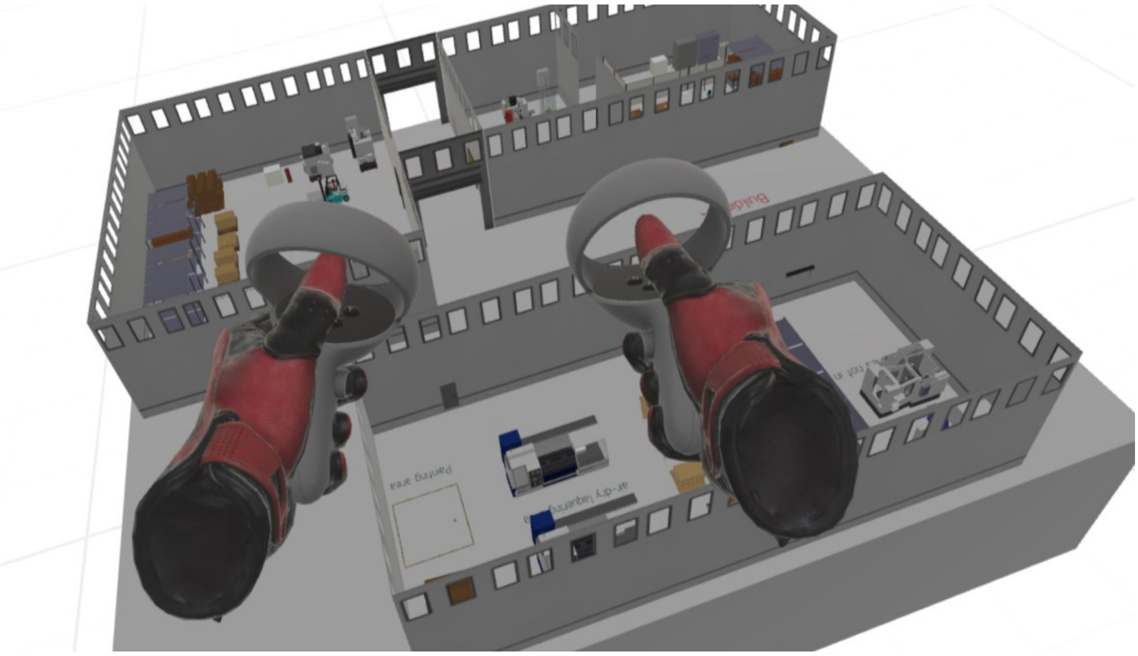


Figure 12 VR layout preview

Figure 13 VR layout preview 1:1 scale

4.1.3 Energy consuming components overview

A great role in energy consumption is played by the condition of the energy-consuming system. Further, the main energy-consuming components on the shopfloor are discussed. First of all, CNC machinery is the main energy consumer in the case study. CNC machinery includes perforation machines (drilling, hole punching), sawing, milling, gluing, and UV or LED lacquer curing machine and their variations. In the appliance classification – CNC machinery belongs to the continuous variable devices.

Next, HVAC system consists of heat, ventilation and air conditioning. Floor heating is used mainly during the cold period of the year and significant consumption growth may be seen when the temperature drops below -5°C. Several strategies may be applied in order to reduce overall electricity consumption. For instance, floor heating may be switched off for short periods. The temperature inside of the building with switched-off floor heating is expected to be satisfactory for approximately 72 hours (only during semi-cold periods, with ambient air temperature from -5°C to +5). Besides the general internal ventilation systems, the vents are installed above each of the manual and machining sanding stations. It is necessary as air cleanliness is one of the perquisites for a safe working environment. Ventilation as well as air conditioning could be considered as a continuous variable device in terms of energy consumption. HVAC retrofitting with the modern and energy efficient components may aid in both energy consumption and CO2 footprint of the company.

Modern lighting (LED lamps) is not energy demanding, however, the change of the whole industrial lighting in the company may require significant investment (significant according to the energy consumption by current lighting). It has been acknowledged that in Puucomp the majority of the lighting has been changed for energy-efficient ones. Along with the energy aspects of the modern lighting systems, it is yet another perquisite, crucial for the safety of the workers.

4.1.4 Implemented solutions to reduce energy consumption

In order to reduce energy consumption and most importantly peak consumptions by the company there has been implemented several solutions which carried different level of success. One of the solutions implemented at the shopfloor has been partial HVAC retrofitting implemented in order to reduce heat loss. In this solution the used air is used to heat the factory. According to the previous studies this method has a sufficient level of support in the reduction in the overall electricity consumption of the enterprise. Yet another method implemented by the company aiming to reduce the heat loss again, is the installation of the sensors for the doors. This method, even though has had positive effect on the keeping warm air inside the building, increased overall electricity consumption.

The installation of capacitor batteries for the machinery to lower its reactive power has been one of the most successful solutions implemented. The economic aspect of the capacitor batteries installation should be taken into account. Figure 14 shows example of the capacitor batteries used by the company. The main purpose of the capacitor battery is to reduce the reactive power and therefore reduce energy consumed by the machine. The specification of the capacitor batteries used are rated power - 50 to 100 kvar, rated frequency - 50 Hz, rated voltage - 400 V, operation conditions - -5/ 40+ °C. Capacitor units with such specifications belong to the low voltage ones. Particularly in the figure 10, wall mounted automatic capacitor banks are presented. In addition to the filtration of the reactive power, such capacitor banks are preventing electrical wiring from early deterioration. (Nokian Capacitors, 2004) ; (Nokian Capacitors Ltd., 2006)

Figure 14 Capacitor batteries used (source: Puucomp)

4.1.5 Energy contract specifics

The electricity contract consists of the contract with the energy delivering company (energy transfer) and the energy provider. The electricity price from the energy provider is not changing according to the time of the day or season, neither there is an additional fee for going above the certain amount of energy consumption. The issue arises with the energy transfer, as additional charges are applied if the consumed energy goes over the set limit per estimated time.

The energy contract consists of two separate parts for each of the buildings, which used to deliver electricity to the company. In order to clarify the issue, electricity bill for one month has been received from the case company. According to the numbers, the cost of the “tehomaksu” or the peak power fee is 87% greater comparing to the day fee during winter. Additionally, the fee for the reactive power input is applied. The solution (described in section 4.1.2) applied by the company capacitor batteries efficiently reducing the reactive power produced by the machinery. The power peak for the building with main processes and machinery has been estimated at 303 kW, while the reactive power peak has been estimated at 94 kvar. However, capacitor batteries installed for major of the machinery enabled reduction of reactive power peak input to the 33,40 kvar. In the second building (painting, lacquering jobs) the power peak energy is estimated as 158 kW. The reactive peak power input (optimised) is 10,40 kvar.

4.2 Energy data set presentation

Further there are presented results from the energy data set analysis as well as framework for the energy management. Additionally, the background on the development of the EVSM for the shop floor is given. However, the accurate EVSM to be developed by the case company.

4.2.1 Data systematisation

Data analysis begins with the definition or statement of the problem aimed to solve with the help of the analysis. The problem has been defined in the research question. Main interest from the company perspective was to visualise the energy profile. In order to produce accurate results, the data should be collected over extended period of time – at least one full calendar year with hourly recordings. Thus, patterns, daily variations, and seasonality in energy consumption may be observed.

Energy data set that has been provided by the company for the period of past three years, where the data has been collected at 24 point per day, resulting in 8760 points a year. During the data cleaning and sorting step, it has been noted that the date format has to be altered. Additionally, open-source databases for the weather conditions have been used. Further, the data has been analysed and structured to see the changes in consumptions that occur due weather conditions, seasonal load on production, daily demand for the energy. Several tools have been selected for the data processing and visualisation, namely R code, Python, Excel data analytics, and statistical tool pack through primarily diagnostic method of a time series.

Interpretation of the findings has been done after the conduction of the data processing. First of all, it was necessary to identify peaks during the day and energy fluctuations as it is a main concern of the case company in terms of energy cost and availability of electricity in the grid. From the graph (Figure 15) it is possible to see that the higher energy consumption falls on to the morning hours from 6 am to 10 am, the next high peak appears when the second shift of the day begins at around 13 pm. After 14 pm energy usage reduces. The situation is similar for both of the buildings. Additionally, during the night hours for the building 2 (building A), between 22.00 pm and 2.00 am the load remain the same. Therefore, it may be assumed that it is the base load (floor heating, HVAC). Slightly different picture can be seen for the first building (building B).

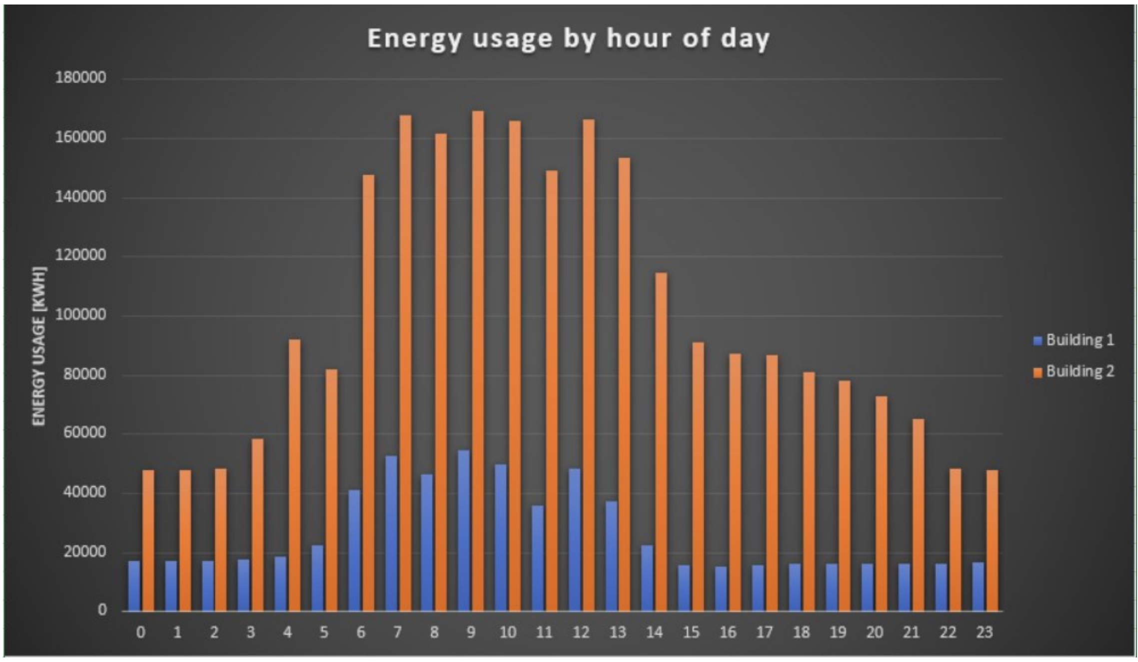


Figure 15 Energy consumption by hour though the day

In building B, there similar energy consumption remains between hours 15.00 pm until 4.00 am. The average load for the building A and B is 92,36 kWh and 24,4 kWh accordingly. Average daily peak consumption for buildings is estimated at 183 kWh – building 1 and 333 kWh building 2. Additionally, it could be seen that there is significant increase in electricity consumption by building A at 4 am, followed by the drop at 5 am and again growth at 6 am.

Next, Figure 16 shows the consumption by the day of the week. It is possible to see that weekly peak in consumption falls onto middle of the week – Tuesday and Wednesday. The overall tendency may be explained thought the workload distribution during the week. The general consumption of energy on Sunday, if none of the production done, could be considered as a base load. However, according to the information gained during interviews with company representatives does not allow such assumption. There are several shifts may occur during the weekends when there are work overload. Therefore, higher accuracy assumptions of the base load may be seen through daily and overall energy consumption throughout the longer periods of time.

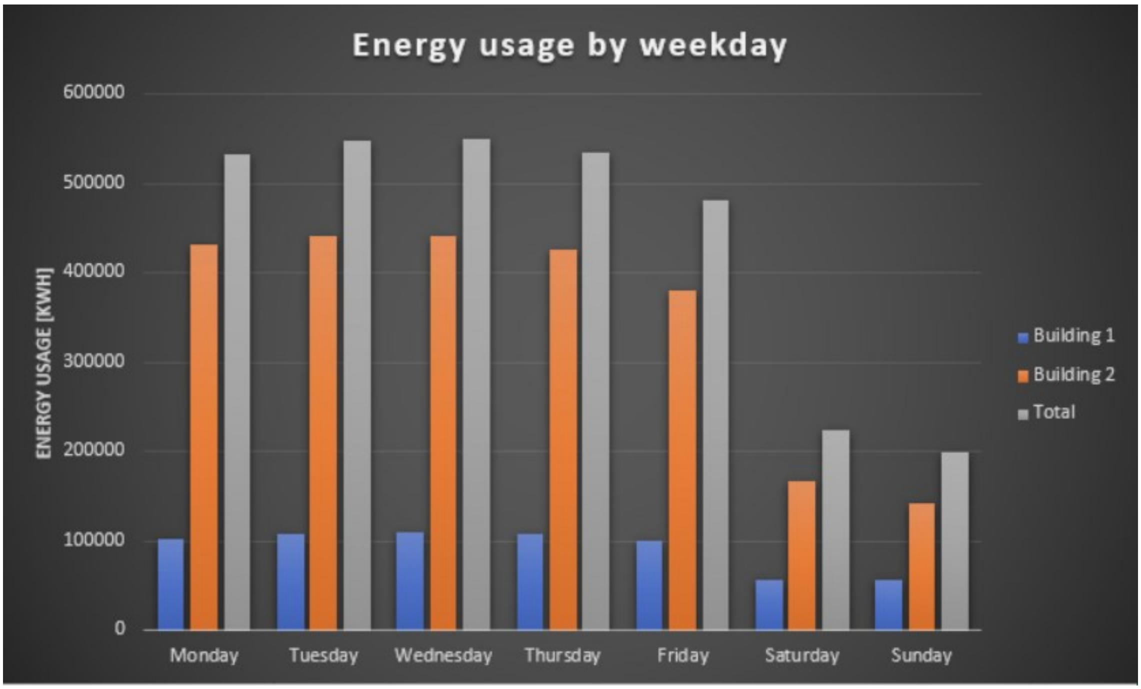


Figure 16 Energy consumption throughout the week

One of such examples represented in Figure 17. The data visualisation is done of average daily assumption for the entire data set, that consists of 3-year data. There the least energy consumption falls on the July when majority of the holidays and leave-offs are takes. Next off-peak consumptions can be seen around the big holiday celebrations, such as Christmas, New Year, Easter, etc. On another hand energy spikes occur during both cold and warm seasons. Although greatest energy consumption spikes may be seen in January, November and December.

Additionally, in Table 2 are summarised key figures that has been calculated from the data set. According to the information from the electricity bill for one-month, peak power during December 2021 is estimated to 303 kW. The calculated peak consumption for the winter period is above 400kWh and during warm period is above 300 kWh. The maximum peak consumption occurred on 25th January of 2019 and has been recorded as 476 kWh.

Table 2 Key figures from the data set

Key figure	Building A	Building B
Base load warm period	4.8 kWh	1.27 kWh
Base load cold period	40.5 kWh	20.17 kWh
Max. peak warm period	Above 300kWh	
Max. peak cold period	Above 400kWh	
Gap to fulfil	~60 kWh	
Absolute peak 25.1.2019	476 kWh	

The base load for both of the buildings is assumed as an electricity demand gap to be fulfilled by alternative source of energy, such as solar power, heat pump, energy storage or wind power.

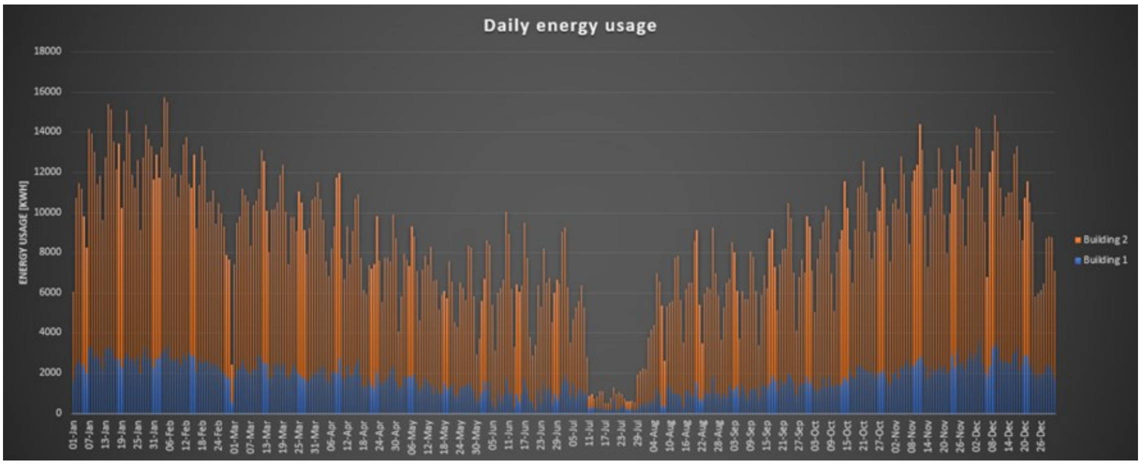


Figure 17 Average daily energy usage

The energy consumption is relatively dependable on the weather conditions, e.g., relative humidity, air pressure and wind speed. Although among rest of the factors, energy usage was found to be very dependable on the temperature, the consumption increase become visible as the temperature goes below 5°C. Figure 18 provides correlation analysis of the energy consumption data set to the open-source data on the weather (IMF, 2022). While air temperature delivers significant raise in the consumption – according to the correlation curve, air pressure and wind speed fluctuation does not result in visible change during what may be considered as normal weather conditions. Comparable situation may be seen in correlation of energy consumption according to the humidity. Nevertheless, the location of the company underlines relatively high level of humidity and wind.

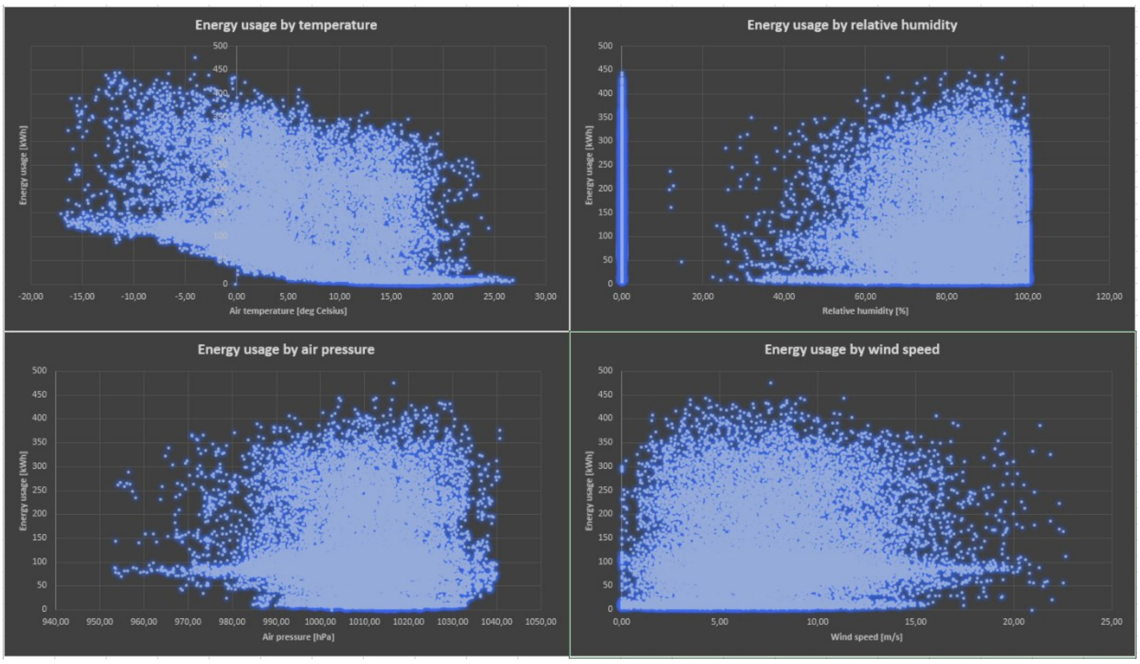


Figure 18 Energy consumption dependencies

4.2.2 Energy loss management during production

An important role in definition of energy consumption profile and production planning is conducted by production strategy. Production strategy could be defined as a pull one. The production is order based with a great level of the customization, meaning that for every order there is going to be a unique strategy for the production of the piece. However, the materials are following similar production route within a shopfloor. The main distinguish lies in the specifics in the perforation of the panel and what are the properties are aimed to achieve.

High level of customization affects the planning of production and therefore increases complexity of energy consumption reducing solutions. One of the approaches to be applied in this particular case may be definition of energy wastes and proposing solutions. (Müller et al., 2014b) (Ohno & Bodek, 2019)

Energy waste	**Management solution**
Overproduction	JIT, pull-production strategy
Transportation within the factory, movement	Layout optimisation
Waiting for process	Rerouting, Batching
Failures or defects in item production	Risk management (human, machinery), training of the stuff
Inventory, warehousing	Pull- production

Table 3 Energy waste (summarised from (Müller et al., 2014b))

Generally, wastes in the enterprise from energy consumption perspective may be divided into overproduction, unnecessary transportation, waiting, defective items, inventory (Table 3). The first waste is overproduction, which is considerably less in push systems, although there are various techniques that can be used to further optimize the production (Müller et al., 2014b). Overproduction in pull systems may be seen in production of spare parts, extra veneer sheets, base wooden panels. In addition to the obvious energy demand for producing the item, overproduction leads to additional transportation and waiting activities, both of which require non-value-adding energy inputs.

Next, transportation and movement withing the shop floor that does not add value includes adjustment of the part, material transfer from one machine to another, etc. Complete removal of time waste may be challenging and only possible in fully automated production. However, reduction of the percent of the time spent on unnecessary transportation and waiting may be done through production rerouting and layout optimisation. (Ohno & Bodek, 2019)

Energy waste concerned with the failures or defects in item production may be caused by various of different reasons. Most common reasons for the defects lie either in machinery condition, poor raw material quality or employee incompetency to complete assigned task. Therefore, the solution may be looked in adhering to the quality management practices. Thus, training of the stuff should be done frequently, preventative maintenance for the machinery, accurate selection of the raw materials supplier may reduce risks of failures and defects.

Next, energy saving activities (ESA) and processes may be allocated through PDCA (Plan-Do-Check-Act) cycle (Figure 19). The first step of the cycle is to "plan" for the change. In this step major considerations about the EnMS system upgrade or implementation should be made. First of all, new strategy concerning energy utilization should be defined. Thus, the required or aimed metrics and current ones need to be established. Current energy consumption may be analysed with the help of EVSM. In addition to the company's internal data analysis team, external energy audit may be used.

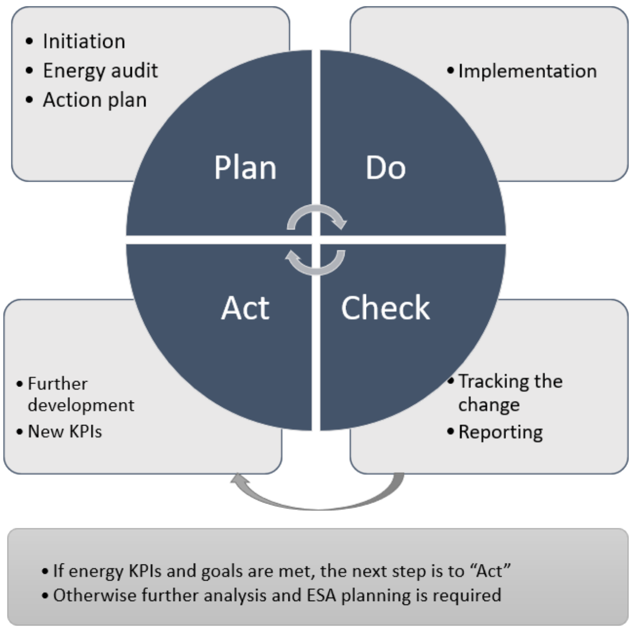


Figure 19 Energy Saving PDCA cycle

Next, the plan with detailed explanation of energy saving actions should be formed. One of the most important steps in the planning process is the definition of roles and responsibilities carried out within energy management. The second step is “Do”, where the planned actions are implemented. Among those actions, there is a need for employee education and training on the energy-saving matters. The actions should be documented for further analysis. Then, in “check” step the KPI are measured. If all of the expected metrics are achieved, the “act” step may be initiated. However, if the metrics are not met, then the process return to the planning phase.

4.2.3 Energy Value Stream Mapping

The EVSM for the case company could be presented as shown in Figure 20. The main processes to be considered in the value adding chain are preparation of boards, sizing, drilling and lacquering/painting. Preparation steps mainly consist of the manual processes such as sanding, gluing, edge attachment. Sizing may be done both manually and with CNC machinery (CNC milling machine, lathes, machining centre). Perforation is done by CNC drilling machine, which contains great variety of the drill bits enabling creation of unique design, perforation, with necessary acoustic properties. The last group of processes is the attachment and mounting profiles manufacturing. The steps in the figure are not always performed in the sequence depicted, but rather present groups of processes with the largest energy consumption to be considered in the EVSM. Furthermore, transportation of raw materials and completed items must be included in EVSM for a complete understanding of the underlying energy flow within a company.

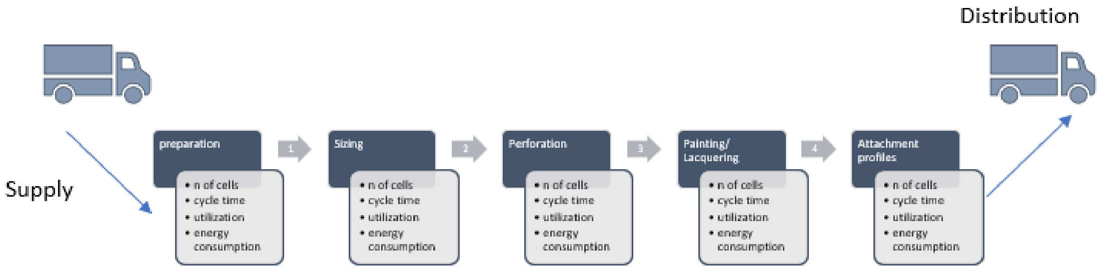


Figure 20 EVSM, main value adding processes

In order to simplify the analysis of the energy flow and possible applicable solutions it was necessary to detect the most energy consuming process and test against the assumptions.

4.2.4 Utilization of the CNC perforation machinery analysis

One of the benefits of the production systems simulation is a possibility of the machinery utilization statistics returns. Figure 21 presents the usage of CNC perforation machine during simulation process. The statistics chart next to CNC perforation machine changes indicators throughout the simulation and after completion of one full cycle it is possible to see realistic picture of the machinery utilization. The chart may be modified and more or less indicators will be visualised on the work field. Next to the simulation field, clarification on the meaning of the colours in the chart given.

Figure 22 resembles the best case scenario for the utilization of the machine, however even in such scenario it is possible to see that busy state in not high, while as idling percentage bar is substantially greater. It may be explained by the need for the adjustments and drill bits changes during the perforation process.

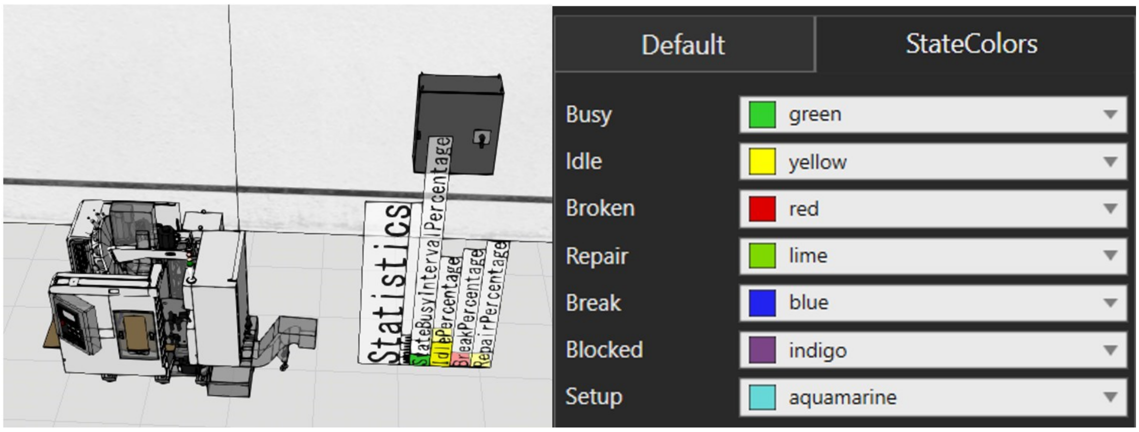


Figure 21 Example of the machinery utilization statistics from VC

Next chart (Figure 22) visualise the utilization of the machinery during one full cycle of the simulation. It is possible to see that with the original settings in the simulation the utilization of the TC-20 (drilling machine) is nearly as high and timely as the rest of the machining processes. However, the pre-setting's in the TC-20 do not consider the realistic timeframe required for perforation process.

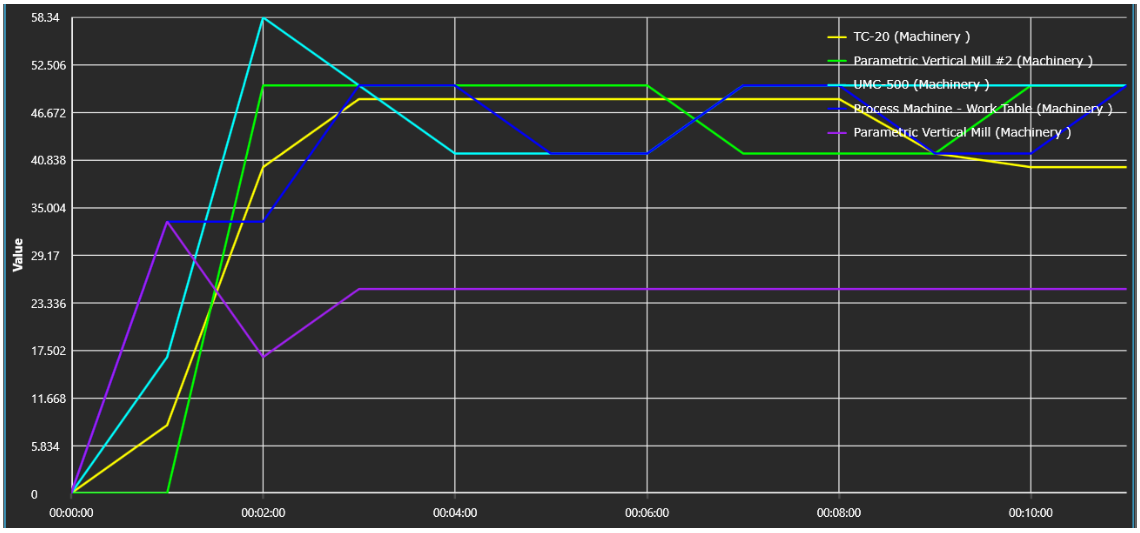


Figure 22 Utilization of the machinery statistics for the last simulation interval

Next, it is possible to see in Figure 23 the comparison of the utilization with the original or predefined machine settings (figure 23 a) and adjusted towards more realistic ones (figure 23 b). There, the change in the utilization percentage changed from 36.9% to 17.3%. Additionally, the production rate of the parts decreased from twelve parts produced during one cycle to 5 parts. The duration of the cycle has remained the same. The idle percentage has visibly grown in comparison to the original case. This way it is possible to assume that the change in the utilization of one of the machine results in the change of the whole systems' operation adding the non-value energy consumption.

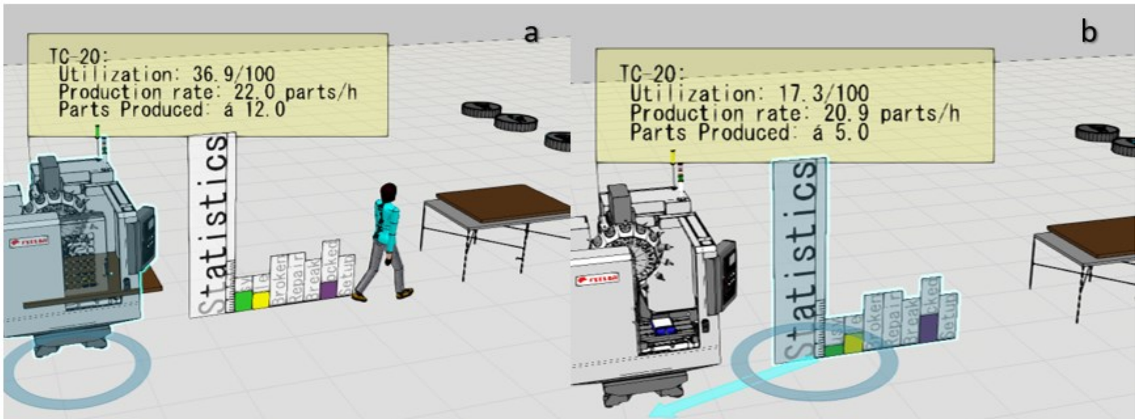


Figure 23 Utilization of CNC perforation machine

Further analysis of the CNC perforation process would require accurate data from the sensors (actual timing in idling, perforation, etc.) and specifications of the machine. However, the available data shows the possibility of the above-mentioned assumptions being verified.

4.3 Layout representation

4.3.1 Initial layout

The early layout (Figure 24 and Figure 25) has been developed with the consideration of the main machining and manual processes. During this step, the goal was to test different production routing and to see whether it plays a significant role in the production rate and machinery utilization. The machinery used in the layout are sawing, drilling or perforation, and milling CNC machines. Additionally, manual processes, such as gluing and assembling the clattering panel from several layers, and sanding are included in the simulation.

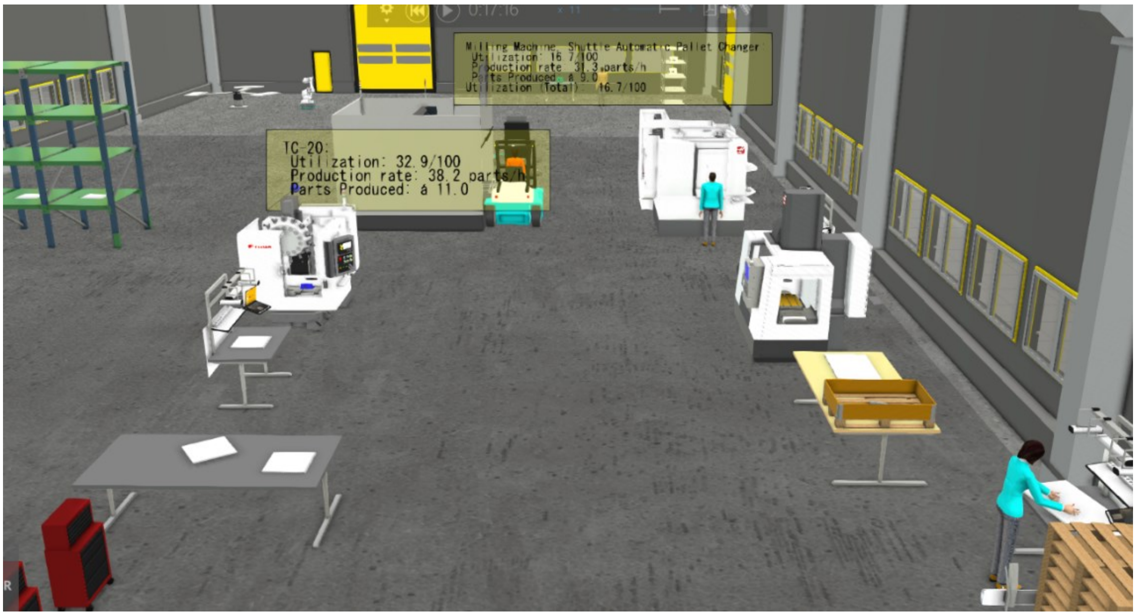


Figure 24 Early layout of the shopfloor

The process flow (Figure 25) begins with the collection of the raw material from the storage, and further transport it to the manual workstation where the material is prepared for the next steps. Next, the piece is forwarded to the machining processes after which the semi-ready product is placed in temporary storage. It is possible to see that transportation of the product is done both manually and with help of the forklift. During this step and with consideration of the additional data from the case company and data gathered throughout the simulation it has been decided to focus on other than production route alteration solutions. Moreover, it has been decided to focus on the CNC drill machine as it is one of the least flexible in terms of scheduling and routing and most energy consuming machine in the manufacturing of the wood clattering panels.

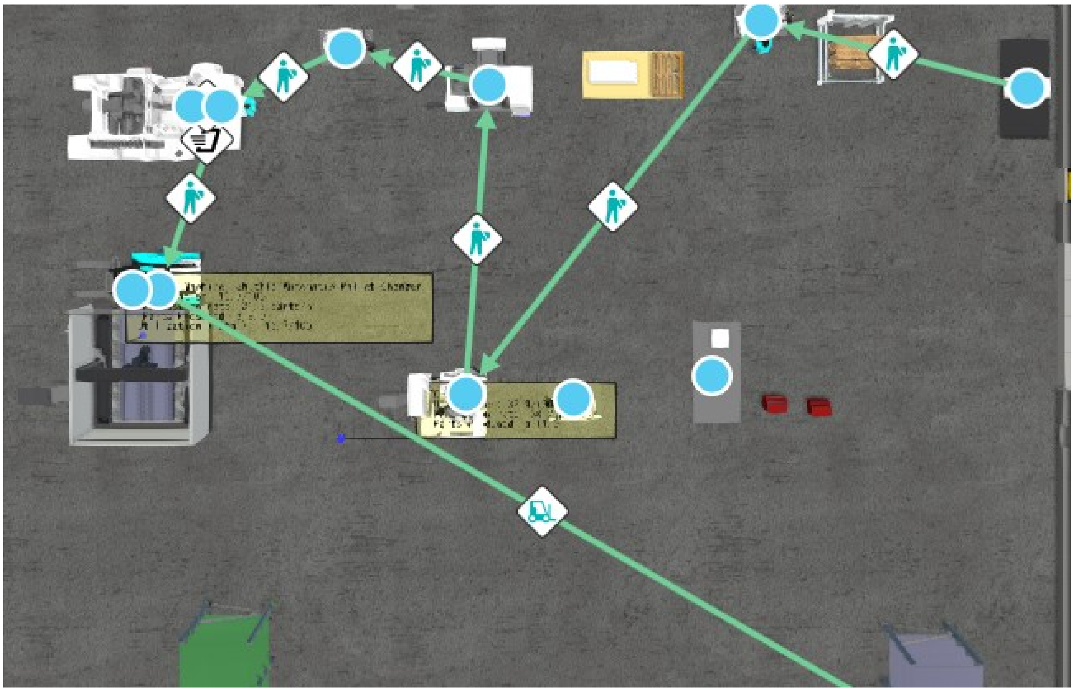


Figure 25 Process flow

In the simulation the processes are connected in a sequence on the shopfloor. The optimization of the process route lies in connection of the processes in a most efficient manner, e.g., least amount of travelling time between stations, least waiting for the process time. There are several sequence types typically seen at the shopfloor, circular type, cross-pattern, etc.

4.3.2 Updated layout

The updated layout includes two production lines or two separate products with own path. In this case the CNC perforation machine has been occupied only by the process (a) of production of an acoustic clattering panel. The second process (b) is the production of a simple interior clattering panel, that consist of two wood material layers. Despite the non-overlapping processes in the TC-20 machine, few of the machines used for both of the processes.

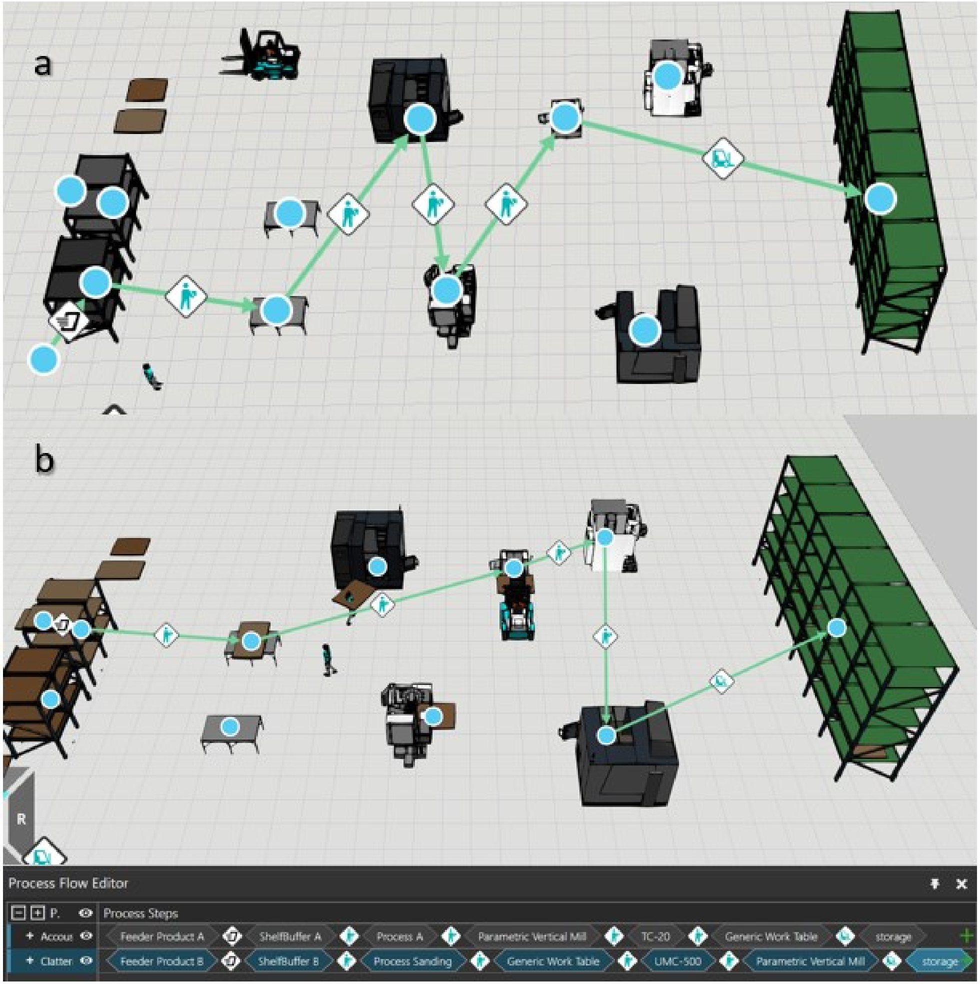


Figure 26 Updated layout process

During further layout development higher accuracy in the machinery placement has been included as well as extension of the processes and amount of the resources utilized. The final layout can be seen in the section 4.1 (figure 10 and 11). Additionally, the detailing as well as the capacitor banks placement has been distributed next to the machinery. However, it is not shown from the layout it is important to notice that above the machinery and manual processes the air vents are situated.

4.4 Alternative solutions for the company

Next, the results and background assumptions for the alternative and mixed solutions are presented. Those are heating pumps comparison, solar energy utilization possibilities, wind energy and batteries.

4.4.1 Heat pump

Heat pump is one of the renewable source solutions to be implemented for the energy utilization optimization. Further (Table 4), different types of heat pumps are compared by the coefficient of performance, requirements for the highest efficiency, and integrability with the existing system. The higher coefficient of performance theoretically aids in the selection of the most suitable type of heat pump. On another hand, a big role in a final decision on the installation affects more factors, for instance - geographical location, surrounding area availability, and size of investment planned. The level of new installation integrity with the existing system defines whether the installation is possible at all. An additional factor may be explained by the installation cost.

First heat pump type is ASHP. The highest efficiency performance by ASHP requires surrounding outside temperature above 0°C, considering this factor the COP of ASHP is estimated between 4 and 6, however considering the cold climate and outside temperature reaching minus 20°C during winter the COP is rather approximates in a range of 1.5 to 3. The disadvantage of ASHP in the Finnish climate is the frost accumulation on the evaporator, due to the low outside temperatures. An advantage of the ASHP is relatively low cost and ease of installation and integration in the existing systems.

Next, ground source heat pump in average produce COP of 3 to 6. In other words, meaning that for every unit of power used, GSHP produce 3 to 6 units of heat (Z. Wang et al., 2021). The benefit of industrial application of GSHP lies in the high efficiency and reliability of the system. Despite the large initial investment in the GSHP system, operating and maintenance costs are moderate. The disadvantage, beside the cost of the system and installation lies in the potential leakage of the refrigerant from coils. When installation of the GSHP is considered, it is necessary to evaluate the amount of available territory and the volume of the building to be heated.

Heat pump type	Requirement for highest efficiency	COP (Coefficient of Performance)	Integrity with existing systems	Reference
ASHP	Outside temperature above 0°C	1.04 – 2.44	High	(Z. Wang et al., 2021)
GSHP	Area availability, soil condition	3.0-6.0	Medium	(Z. Wang et al., 2021)
SAHP	Sufficient solar radiance	2.5 - 6	Medium	(Badiei et al., 2020; Huan et al., 2019; Z. Wang et al., 2021) (Lin, Y. et al., 2022)
EAHP	Acceptable condition of the building and all systems within	2.9-3.4	High	(Mikola & Kõiv, 2014; Shirani et al., 2021; Todorovic, 2012)

Table 4 Comparison of heat pumps

Solar assisted heat pump would enable significant reduction of the overall energy consumption. The coefficient of performance of the SAHP highly dependable on the coupling heat pump and the type of the SAHP system. Additionally, one of the disadvantages of the SAHP lies in the complex control system. On average the range of SAHP COP lies in 2.5 to 6.57, more realistic COP for the northern climate may be estimated at 3.5-4. Wider range of energy source (ambient air or ground heating, and solar radiance) enable adequate system performance even in the cold climate.

Majority of the studies for the exhaust air heat pump (EAHP) is done for its efficiency for the residential buildings. In industrial case EAHP is rather considered in the combination retrofitting HVAC systems. The COP of EAHP is estimated to 2.9-3.4, the disadvantage of such system lies in the high dependency of the condition of the building isolation and air circulation/ ventilation systems.

4.4.2 Solar power

The most favourable utilization of solar energy might be seen in the form of outsourcing the energy harvesting, e.g., renting the roof space for the solar panels for the interested party. The area of the roof is approximately 4392 m^2, however the condition of the roof and availability of the open space needs to be evaluated. During the DIGI-MODE project, there has been developed a digital twin solution for solar panel installation planning according to the location of the building and rooftop area. Nevertheless, according to the simulation of the solar energy for Kristiinankaupunki area, which can be seen in Figure 27, there are adequate conditions for solar energy harvesting throughout the year. Most of the monthly energy output may be seen between March and September, resulting in more than 6 months of sufficient solar radiation.

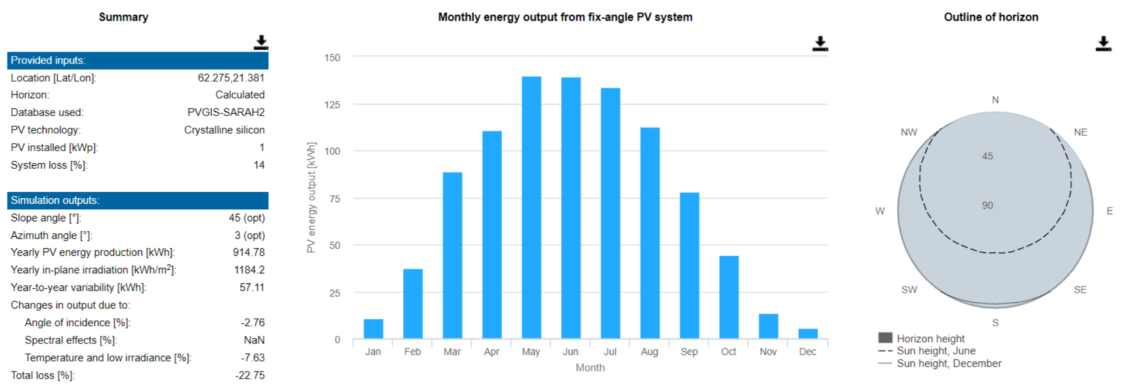
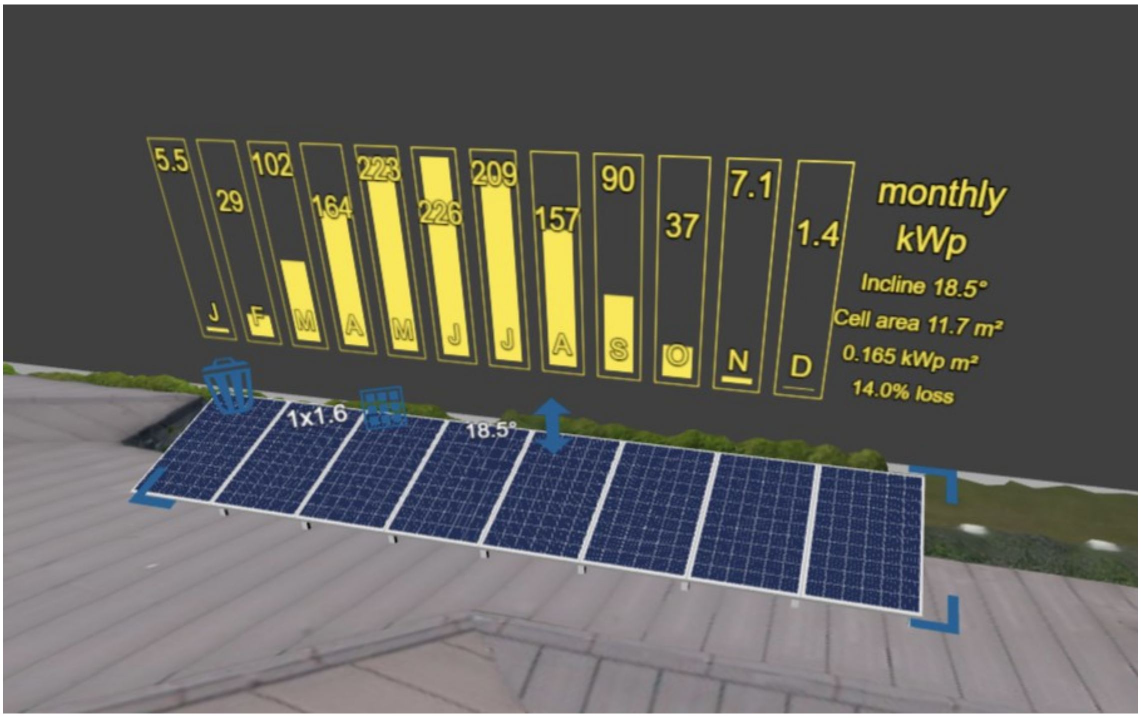


Figure 27 Solar power simulation for Kristiinankaupunki area for one PV panel (IMF, 2022)

During the DIGI-MODE project there has been developed service, architect, and construction digital twins. Solar panel planner (Figure 28) is one of the developed extensions to the architect DT. The solar panel planner enables the placement of the solar panels on the roof of the building, visualising the possible energy harvesting according to the panels' amount and positioning. A solution could aid the energy companies, which are interested in rooftop leasing and the company itself in the case of installation of solar panels for energy harvesting. Alternatively, solar energy might be used in cooperation with the heat pump, or other words, Solar Assisted Heat Pump solution.



Vaasan yliopisto UNIVERSITY OF VAASA · NOVIA · VAMK · Åbo Akademi University · experience lab · European Union European Regional Development Fund · Leverage from the EU 2014–2020 · Regional Council of Ostrobothnia

Figure 28 Solar panel planner (has been developed within DIGI-MODE project)

On the other hand, solar energy might be used in cooperation with the heat pump, or in other words, Solar Assisted Heat Pump solution.

4.4.3 Wind power

The use of wind energy by the enterprise may not only affect positively the carbon footprint of production but also reduce the cost of overall electricity consumption. One of the solutions concerning wind energy for the case company may be seen in purchasing green wind energy from the grid. There are several options considering the supplier of the electricity besides the current energy supplier.

The number of wind turbines installed in 2022 as well as wind turbine capacity has increased significantly compared to the previous year. During 2021 there has been produced 8000 GWh, while as already in 2022 annual wind power production resulted in nearly 12000 GWh (FWPA, 2023). Therefore, wind energy rates, in contrast to basic electricity, has a great potential to decrease during the upcoming summer. However, the cost of renewable wind energy is heavily reliant on weather conditions and consequently the amount of electricity produced by wind farms. Furthermore, another option for long-term wind energy use is a PPA (power purchase agreement), in which the company purchases electricity from the energy supplier for a set length of time (10 to 20 years) (FWPA, 2022). The benefit of such agreement would be predictability of the prices and stability of the supply.

4.4.4 Energy storage

Further there are presented suitable batteries solution for the case. The main aspect of the selection of the battery lies in the ability to deliver necessary energy capacity to reduce peak consumption, while keeping the cost of the battery feasible. There are few options available. One of such is Tesla powerpack conducts power up to 130 kW per unit with energy capacity of 232 kWh. In terms of the flexibility of the solution, tesla powerpack is one of the most suitable one, as it has variation in the amount of stackable power units.

Overall System Specs

AC Voltage	380 to 480V, 3 phases	Energy Capacity	Up to 232 kWh (AC) per Powerpack
Communications	Modbus TCP/IP; DNP3; Rest API	Operating Temperature	-30°C to 50°C / -22°F to 122°F
Power	Up to 130 kW (AC) per Powerpack	Enclosures	Pods: IP67 Powerpack: IP35/NEMA 3R Inverter: IP66/NEMA 4
Scalable Inverter Power	From 70kVA to 700kVA (at 480V)	System Efficiency (AC) *	88% round-trip (2 hour system) 89.5% round-trip (4 hour system)
Depth of Discharge	100%	Certifications	Nationally accredited certifications to international safety, EMC, utility and environmental legislation.
Dimensions	Powerpack Unit Length: 1,317 mm (50.9 in) Width: 968 mm (38.1 in) Height: 2,187 mm (86.1 in) Weight: 2,199 kg (4,847 lbs) Powerpack Inverter Length: 1,044 mm (41.1 in) Width: 1,394 mm (54.9 in) Height: 2,191 mm (86.2 in) Weight (max): 1,120 kg (2,470 lbs)		

* Net Energy delivered at 25°C (77°F) ambient temperature including thermal control

Figure 29 Tesla Power Wall specifications (source: (Tesla, Inc., 2022))

4.4.5 Conclusion on the alternative solutions

The table below (Table 5) represents a comparison of the solutions to the stated problem. Solutions are compared from the perspectives of the need for the investment, their feasibility, level of adaptability in the current process and ability to fulfil the requirement for the energy consumption/ tackle the peak electricity consumption. The rating is done from 0 to 10, where 0 is the least positive and 10 is the most positive influence of the solution for the electricity consumption problem tackling. In the case of the investment rating 0 to 10 is followed, where 0 is the least amount of investment needed and 10 is the maximum investment. The indicators in the table are based on the data gained throughout the research and literature on the topic.

Solution	Investment	Feasibility	Adaptability	Ability to fulfil consumption requirement	Companies' rating
Rerouting of the production	3	7	6	- (peaks)	3
Solar panels	5	7	9	7	8
Heat Pump	8	6	5	7	7
Wind turbine	8	5	7	7	4
Energy storage	10	6	7	9	3

Table 5 Comparison of the approaches for the problem

The first solution is the rerouting of the production/ distribution machinery used throughout the day. Such a solution carries relatively low investment while enabling delivering the immediate result in terms of energy consumption peaks reduction. The adaptability of such a solution is highly dependent on the operation and production management systems within the company. Thus, accurate and effective planning of the change (change management) as well as energy management activities increases the level of adaptability. In the particular case in the study, rerouting has not been seen as a favourable solution. That may be because the high level of product customization as well as tight deadlines do not give enough space for possible miscalculations and idling during the change process.

The next solution is solar energy utilization. Further, scenarios for renewable energy mix will be provided, in which the integration of solar energy with other solutions will be addressed in depth. Nevertheless, sole application of the solar energy for the industrial use has been considered as a feasible solution in given circumstances. The next indicators are a moderate investment and high adaptability. Additionally, according to the calculations, solar energy would be able to fulfil the electricity consumption for floor heating. Solar-assisted heat pumps or rooftop leasing, on the other hand, may produce greater results and be more beneficial for the application. Along with SAHP, among the rest of the heat pumps, the geothermal vertical heat pump is the most suitable solution, considering the energy demand for the floor heating and ambient air temperature fluctuations throughout the year. Vertical coil positioning would enable greater stability of the heating because of the freezing depth of the soil and therefore level of geothermal heat available for absorption.

Installation of the own wind turbine by the company would result in the overall optimization of energy consumption. A small-scale wind turbine would be able to produce enough energy for office needs (e.g., electronics, appliances, lighting). However, the amount of investment in the wind turbine that would be able to produce sufficient energy for the machinery is not feasible. Integration of the wind power (from wind turbine) in the companies' energy structures as well as solar power might be concerned with the need of complex control systems, but the adaptability of the solution is relatively high. The range of wind energy utilization alternatives (e.g., micro and small-scale windmills, outsourcing of energy harvesting, share in wind energy production) could explain the level of adaptability.

Energy storage systems are considered with a need for significant investment. The rating of the feasibility is estimated as sufficient, however it is often not seen by the enterprises as such. In addition to the high cost of the systems, the lifetime of the batteries is limited to certain timeframe (20 years). On a contrast with other solutions that can be updated and adjusted to improve efficiency, batteries should be replaced. Despite these conclusions, ESS capacity has the potential to tackle the problem of peak energy usage while also lowering overall electricity costs.

4.4.6 Energy mix scenario

Throughout the process of the study, it has been repeatedly noted that the resolution of the energy consumption issues by the enterprise requires a complex approach. Further, there are presented energy mix scenarios that may cover more aspects as well as ensure the sustainability of the solution. The main trend in energy optimization is aimed at the more cautious use of resources and the move toward renewable energy sources.

Scenario 1

Scenario 1 (Figure 30) consist of several components, e.g., solar panels, wind energy and additional energy storage. In such scenario peaks in energy consumption are prevailed through the additional energy storage. Energy storage is used to store the "cheap" energy during the night and utilize it during the morning hours. This way the fluctuation in the price of the energy due to overcoming the limit could be reduced. Due to the fact that one of the issues lies in the lack of electricity in the grid, an additional energy supplier may be considered. The utilization of the solar energy may be seen in the support of the floor heating or fully covering the required energy for the heating purposes. An additional important aspect of this and the next scenario lies in the continuous EVSM and therefore tracking the success level of implemented solutions.

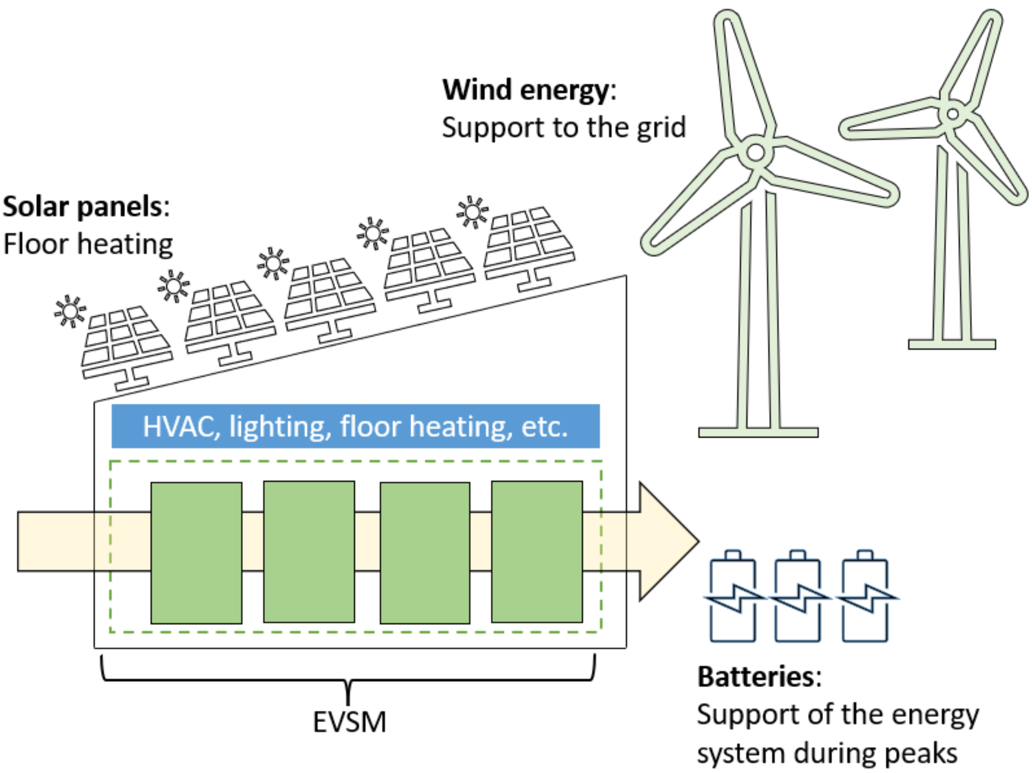


Figure 30 Mixed solution scenario 1

Scenario 2

In the first scenario, solar panels are purchased and installed at the cost of the case company. The second mixed solution (Figure 31) proposes that the roof area of the buildings would be rented out to the energy company that in its turn use solar panels to generate electricity. Unlike in the first solution, the solar panel's installation and upkeep do not require investment from the case company and are rather beneficial in terms of energy cost. The gap or profit from renting out the roof area for the solar panels can either be used for the purchase of solar energy or investment in other energy sources.

Another element of the second scenario is the installation of a geothermal source heat pump. Considering the climate conventionally available geothermal heat pumps would be able to cover the heating and cooling of buildings throughout warm and cold periods. The disadvantage of geothermal heat pump in comparison to other heat pumps may be seen in higher investment, however it has greater efficiency in the cold climates. In addition to the GSHP, further enhancement of the HVAC systems or integration of EAHP.

Similar to the first scenario, the solution for the energy peaks is seen in the use of the additional energy storage and an upgrade of the capacitor batteries to the more modern ones.

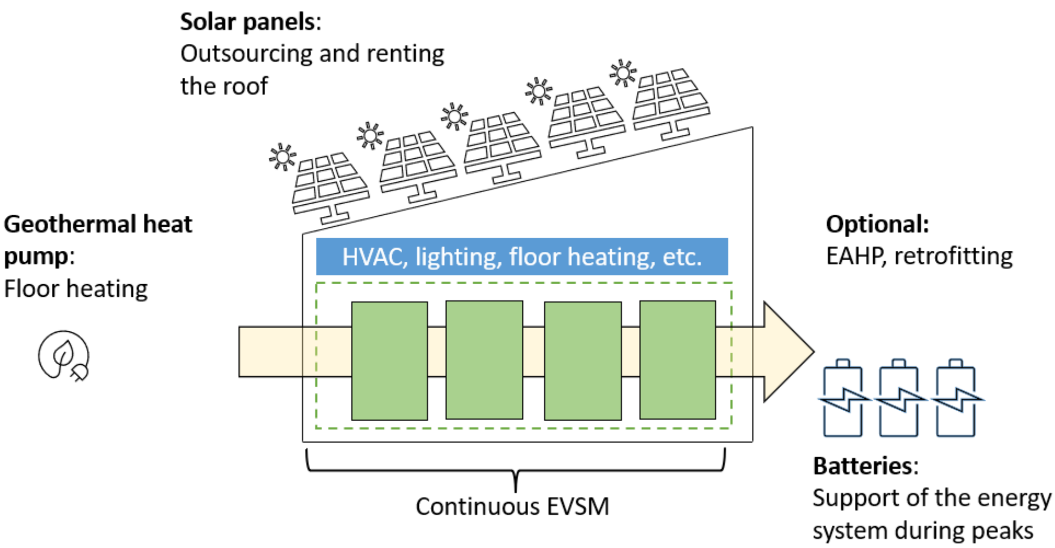


Figure 31 Mixed solution scenario 2

5 Conclusion

This study has been completed based on the energy consumption optimization case for the Finnish wood clattering panels manufacturer - Puucomp. Throughout the communication with the company main concerns have been acknowledged. Nonetheless, this study investigated general energy optimization opportunities for the industries from a management perspective and through possible technological advancement.

Solution for this specific case, as well as generally cases with energy optimization, require a complex approach. It could often be seen that companies are applying only one direct solution aimed at one specific area. Such an approach does not allow to reach sufficient energy efficiency, nor to fulfil expectations for the cost reduction spend of electricity. Data analyses done based on the provided list of electricity consumption records throughout the last 3 years, enable to propose that a significant amount of electricity is used for ventilation/ air-conditioning, lighting, and floor heating. Further, these areas have been investigated for the possible alternatives and feasibility of the implementation of new solutions.

One of the main concerns of a case company has been the resolution of peak consumption. It has been identified that peak consumption is appearing during the morning hours, when the majority of the machinery has been turned on, including lighting, HVAC, etc. Focusing solely on the machinery operation, it has been possible to propose, that slow and step-by-step turning-on of the machinery could already positively affect the overall peak. Another solution for the significant peak consumption reduction could be seen in the rerouting of the production and use of the machines per demand.

The simulation of the shopfloor of building A has been created. The simulation includes the main CNC machinery and human processes, enabling the simulation of the current state and the future state of the shop floor. Furthermore, simulation of the shopfloor has been used to visualize possible changes in machinery utilization with a change of the route or different scheduling. Shopfloor analysis required investigation of the existing machinery and its energy consumption profiles. Unfortunately, in some of the cases, machinery cannot be changed or enhanced in terms of its energy efficiency, therefore its maximum load needs to be considered for the analysis. The most customizable, time-consuming, and least flexible part of the production of a wood clattering panel is the creation of the perforation. Therefore, the analysis of the CNC drill machine operation has been done.

Despite proposed possible solutions for the optimization of energy consumption, in the cases when there is a lack of electricity in the grid, alternative solutions must be looked at. Such solutions are, for instance, the use of renewable energy sources – solar energy, heat pumps as well as large energy storages.

Answering the research questions,

1. What is the energy consumption profile for the manufacturing of a wood clattering panels?

The energy data consumption profile has been defined through analysis of the energy consumption data for the duration of the 3 previous years. The data availability for a long period enabled the determination of the energy consumption pattern throughout the day, seasonal changes in consumption as well as its dependency on the weather conditions. It has been determined that ambient temperature has the most influence on the consumption profile. During a cold period, when the outside temperature reaches minus five degrees, the consumption of electricity increases due to the need for additional space heating. Therefore, a significant raise in the electricity profile may be seen during abnormal (below minus twenty-five degrees) external temperatures. Besides the ambient temperature, there has not been a defined significant dependency in electricity consumption on air pressure, humidity, or wind speed.

There are two shifts during the working day, which has been visible from the energy consumption profile. The greater consumption peak has been seen during the beginning of the first shift of the day and a minor peak during the beginning of the second shift. Yet another increase in energy consumption occurs during periods with a heavier workload and deadlines.

2. What solution can be used to minimize and optimize it?

Possible solutions to minimize overall consumption demand lies in the integration of energy-efficient devices (e.g., lighting, smart switches, etc.) as well as reasonable use of floor heating. An additional step could be seen in the enhancement of the existing HVAC retrofitting system. Concerning peak consumptions, the solution lies in the combination of distribution of the use of the machines with high energy consumption during the longer time along with enhanced system of reactive power compensation energy storages.

3. Can Digital Twin concept be used in energy case?

Development of the digital twin of the production line along with the data from the IoT sensors would enable creation of the accurate EVSM and simulation/ planning for change without the production process disruption. Digital twin technologies application would allow companies to access wider range of the solutions in terms of the tight production schedule. Additionally, it is possible to propose that application of DT technologies would enable risk mitigation.

4. What are the limitations of Digital Twin implementation for small and medium enterprises?

Limitations of the DT implementation for the SMEs lies first of all in the level of the technological awareness, as often there plenty of confusions concerning the definition and applicability of digital twin. It is often appearing that company representatives do not recognize possible use of DT technologies for their specific case until some ideas are proposed and similar cases are displayed. Yet another concern lies in the cost of the technology and therefore development of the functioning DT. Not only the development of the DT, but the upkeep costs for the software, hardware, and knowledgeable employees might become an obstacle for the SMEs.

From the perspective of the technology – digital twin is based on the data, which either has been collected over the time or there is real-time transfer of the data from the sensors (IoT) for instance. Therefore, lack of the data available from a process or an enterprise can be one of the limitations to the development of the digital twin. Moreover, the data available is typically unstructured, contains significant errors, and requires complex cleaning and processing even before it can be examined. Another issue of data is privacy and security concerns. The high reliance of DT on data is concerned with the risk of potential data breaches. This can expose sensitive information or cause data manipulation, threatening the digital DT's accuracy and reliability.

Another aspect of the DT creation lies in the virtual environment development. According to Grieves' definition, DT does not need to replicate visually the real-world environment, however visualisation enhance understanding and clarity of the processes. Additionally, from the perspective of VR utilisation, it can be used to demonstrate clattering panels to potential customers. Further, VR simulation improvement would enable customers to preview different products and configurations, visualize how it will look in a specific location, and to customize products to fit the needs. This has the potential to improve the sales process and increase customer satisfaction.

5.1 Managerial implication

Optimization of the energy consumption is one of the concerns for manager of an enterprise due to the fact that electricity consumption is concerned with significant utilization of companies' resources, and it does affect companies' profits. Resolution of the energy consumption issues for the manufacturing and production systems requires complex approach which includes optimisation activities as well as proper energy management. Managerial solution for the specific problem lies in seeking for the elimination of the energy waste options as well as integration of sustainable solutions. This could be summarised in need of the implementation of LEAN management practices.

Elimination of the wastes during production does positively affect the overall energy consumption. Although, one of the overlooked factors in the definition of the wastes could be named – human factor and its effect on the non-value adding working time. Human productivity is highly affected by the understanding of different aspects of the work (e.g., every minute of idle time consumes a certain amount of energy), tiredness (e.g., overworking, high frequency of the time shift change, etc.), motivation. In overall, the proportion of the ability of a worker to be more present and attentive at work is linear to the coverage of Maslow's pyramid of human needs.

New machinery and complete renovation of the HVAC system may be required for the significant reduction of the overall electricity consumption and possibility of one sole solution integration for the support. The upgrade of the machinery or its total change for the newer ones is the next step to be taken in the enhancement of the energy efficiency. However, few aspects need to be considered along with such decisions. For instance, whether the new CNC machinery is able to perform up to expected metrics and the after useful lifetime expired machinery processing. Among anticipated changes in the machinery, the chemical compound glue used for the assembly of the panels may be improved, so that a lower temperature would be required for the process. Therefore, less electricity would be used for the preheating. Additionally, the possibility of combinatory machines with more than one process coverage would significantly aid in the energy efficiency of manufacturing.

During the discussion with the company the results have been presented for the CEO and production manager. Findings of the study has been seen useful and some of the proposed solutions have been not seen as most feasible just yet, although those may be beneficial for the new builds. The price of the energy storage solution is relatively high, however, that is when the price of the energy remains consistent, and no major increases are expected. In a situation when the market price of energy is unstable with a tendency to grow, and the technology is becoming less expensive and more accessible the investment into energy storage systems may become more acceptable. The new factory building will be completely heated with a geothermal heat pump. An additional edge derived from the proposed solutions is the production of the energy not just for the company needs but for the profit. Solar panels may be utilized for this purpose. Thus, partially the energy harvested from the solar panel system will be used for the company needs and the rest may be sold to the grid.

Yet another question is the sustainability of the implemented solutions, highly affecting the reputation of the company. Additionally, the state regulations and directives promoting the move towards greener energy and reduction of emissions. This thesis may be used further for the carbon footprint estimation and lifecycle assessment.

6 Discussion

Electricity production and consumption are one of the most crucial questions both for industries and average consumers. Along with the new technologies development and price of the technologies becoming accessible, the mindset of the population changes towards more cautious resource utilization. Therefore, it is possible to see that green and sustainable companies are preferred to inexpensive, yet polluting energy / products/ services.

Some of the questions arise when considering the life cycle of the solutions. Feasibility and reliability are among the most important ones. Yet another question is concerned with the processing of the solutions after its useful lifetime. A great concern might be seen in the use of batteries or chemical energy storage. Although the useful lifetime of commercially available energy storage has been extended up to 20 years on average, on a large scale it is very pollutive. However, on a small scale, the local or enterprise implementation of batteries may seem like a sustainable solution. The move towards more green and sustainable solutions for the newly built factories is highly government regulated as well as the existing ones. The difference comes when and how much change is needed to fulfil regulations. Therefore, one of the further developments in the energy optimization area could be the creation of ESS with a longer lifetime and enhancements in the after-useful lifetime processing of batteries.

6.1 Scope for future work

Further development can be seen in creation of the digital twin framework for the SMEs and in particular energy DT. Energy questions are not expected to become less important in the near future, therefore there is plenty of space for further research in the different energy optimization approaches.

References

Abbassi, I. el, Labadi, K., Hamaci, S., & Darcherif, A. (2015). Energy Management and Optimization in Manufacturing Systems. *Proceedings of the Asia Pacific Industrial Engineering & Management Systems Conference 2015*, *December*.

Aktaş, A., & Kirçiçek, Y. (2021). Solar Thermal Systems and Thermal Storage. In *Solar Hybrid Systems* (pp. 127–137). Elsevier. https://doi.org/10.1016/b978-0-323-88499-0.00006-9

Al-Ababneh, M. M. (2020). Linking Ontology, Epistemology and Research Methodology. *Science & Philosophy*, *8*(1). https://doi.org/10.23756/sp.v8i1.500

Amiryar, M. E., & Pullen, K. R. (2017). A review of flywheel energy storage system technologies and their applications. In *Applied Sciences* (Vol. 7, Issue 3). Balkan Society of Geometers. https://doi.org/10.3390/app7030286

Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., & Bertsch, S. S. (2018). High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. In *Energy* (Vol. 152). https://doi.org/10.1016/j.energy.2018.03.166

Badiei, A., Golizadeh Akhlaghi, Y., Zhao, X., Shittu, S., Xiao, X., Li, J., Fan, Y., & Li, G. (2020). A chronological review of advances in solar assisted heat pump technology in 21st century. In *Renewable and Sustainable Energy Reviews* (Vol. 132). https://doi.org/10.1016/j.rser.2020.110132

Barbosa, C., & Azevedo, A. (2017). Hybrid Simulation for Complex Manufacturing Value-chain Environments. *Procedia Manufacturing*, *11*. https://doi.org/10.1016/j.promfg.2017.07.270

Bekhta, P., Krystofiak, T., Proszyk, S., & Lis, B. (2018). Surface gloss of lacquered medium density fibreboard panels veneered with thermally compressed birch wood. *Progress in Organic Coatings*, *117*. https://doi.org/10.1016/j.porgcoat.2017.12.020

Benali, M., Hammache, A., Aubé, F., Dipama, J., & Cantave, R. (2007). Dynamic multi-objective optimization of large-scale industrial production systems: An emerging strategy. *International Journal of Energy Research*, *31*(12). https://doi.org/10.1002/er.1329

Borowski, P. F. (2021). Digitization, Digital Twins, Blockchain, and Industry 4.0 as Elements of Management Process in Enterprises in the Energy Sector. *Energies*, *14*(7). https://doi.org/10.3390/en14071885

Broby, D. (2022). The use of predictive analytics in finance. *The Journal of Finance and Data Science, 8*, 145-161. doi:https://doi.org/10.1016/j.jfds.2022.05.003.

Bryman & Bell. (2015). Business Research Methods - Alan Bryman, Emma Bell - Google Books. In *Business Research Method*.

Burgess, N., & King, J. A. (2001). Navigation in Virtual Space: Psychological and Neural Aspects. In *International Encyclopedia of the Social & Behavioral Sciences*. https://doi.org/10.1016/b0-08-043076-7/03564-6

Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). Wind Energy Handbook, Second Edition. In *Wind Energy Handbook, Second Edition*. https://doi.org/10.1002/9781119992714

Canlas, I. P., & Karpudewan, M. (2020). Blending the Principles of Participatory Action Research Approach and Elements of Grounded Theory in a Disaster Risk Reduction Education Case Study. *International Journal of Qualitative Methods*, *19*. https://doi.org/10.1177/1609406920958964

Capehart, B. L., Kennedy, W. J., & Turner, W. C. (2020). Guide to Energy Management. In *Guide to Energy Management*. https://doi.org/10.1201/9781003152002

Carroll, P., Chesser, M., & Lyons, P. (2020). Air Source Heat Pumps field studies: A systematic literature review. In *Renewable and Sustainable Energy Reviews* (Vol. 134). https://doi.org/10.1016/j.rser.2020.110275

Chahartaghi, M., Kalami, M., Ahmadi, M. H., Kumar, R., & Jilte, R. (2019). Energy and exergy analyses and thermoeconomic optimization of geothermal heat pump for domestic water heating. *International Journal of Low-Carbon Technologies*, *14*(2). https://doi.org/10.1093/ijlct/cty060

Chen, J., Dowman, I., Li, S., Li, Z., Madden, M., Mills, J., Paparoditis, N., Rottensteiner, F., Sester, M., Toth, C., Trinder, J., & Heipke, C. (2016). Information from imagery: ISPRS scientific vision and research agenda. *ISPRS Journal of Photogrammetry and Remote Sensing*, *115*. https://doi.org/10.1016/j.isprsjprs.2015.09.008

Chen, T., Jin, Y., Lv, H., Yang, A., Liu, M., Chen, B., Xie, Y., & Chen, Q. (2020). Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems. In *Transactions of Tianjin University* (Vol. 26, Issue 3, pp. 208–217). Tianjin University. https://doi.org/10.1007/s12209-020-00236-w

CIRP Encyclopedia of Production Engineering. (2020). In *CIRP Encyclopedia of Production Engineering*. https://doi.org/10.1007/978-3-642-35950-7

Corberán, J. M., Cazorla-Marín, A., Marchante-Avellaneda, J., & Montagud, C. (2018). Dual source heat pump, a high efficiency and cost-effective alternative for heating, cooling and DHW production. *International Journal of Low-Carbon Technologies*, *13*(2). https://doi.org/10.1093/ijlct/cty008

Crawford, A. J., Huang, Q., Kintner-Meyer, M. C. W., Zhang, J. G., Reed, D. M., Sprenkle, V. L., Viswanathan, V. v., & Choi, D. (2018). Lifecycle comparison of selected Li-ion battery chemistries under grid and electric vehicle duty cycle combinations. *Journal of Power Sources*, *380*. https://doi.org/10.1016/j.jpowsour.2018.01.080

Creswell, J. W. (2003). Creswell, J.W. (2003). Chapter One, "A Framework for Design." *Research Design Qualitative Quantitative and Mixed Methods Approaches*. https://doi.org/10.3109/08941939.2012.723954

Darke, P., Shanks, G., & Broadbent, M. (1998). Successfully completing case study research: Combining rigour, relevance and pragmatism. *Information Systems Journal*, *8*(4). https://doi.org/10.1046/j.1365-2575.1998.00040.x

David, R., & Alla, H. (2010). Discrete, continuous, and hybrid petri nets (second edition). In *Discrete, Continuous, and Hybrid Petri Nets (Second Edition)*. https://doi.org/10.1007/978-3-642-10669-9

Deng, J., Wei, Q., Liang, M., He, S., & Zhang, H. (2019). Does heat pumps perform energy efficiently as we expected: Field tests and evaluations on various kinds of heat pump systems for space heating. *Energy and Buildings*, *182*. https://doi.org/10.1016/j.enbuild.2018.10.014

Diaz C., J. L., & Ocampo-Martinez, C. (2019). Energy efficiency in discrete-manufacturing systems: Insights, trends, and control strategies. In *Journal of Manufacturing Systems* (Vol. 52). https://doi.org/10.1016/j.jmsy.2019.05.002

European Comission. (2022). *Energy efficiency targets*. Retrieved from https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-targets_en

Eurostat. (2022, February). *Energy statistics - an overview: Final energy consumption*. Retrieved 2022, from Eurostat Statistics Explained: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption

Fan, Y., Zhao, X., Han, Z., Li, J., Badiei, A., Akhlaghi, Y. G., & Liu, Z. (2021). Scientific and technological progress and future perspectives of the solar assisted heat pump (SAHP) system. *Energy*, *229*. https://doi.org/10.1016/j.energy.2021.120719

Flores-Garcia, E., Wiktorsson, M., Jackson, M., & Bruch, J. (2016). Simulation in the production system design process of assembly systems. *Proceedings - Winter Simulation Conference*, *2016-January*.

FWPA. (2022). *PPA (power purchase agreement)*. Retrieved from tuulivoimayhdistys: https://tuulivoimayhdistys.fi/en/wind-power-in-finland-2/ppa-power-purchase-agreement/what-is-ppa

FWPA. (2023). *Finnish WInd Power Statistics 2022.* Retrieved 2023, from https://tuulivoimayhdistys.fi/media/finnish-wind-power-stats_2022-12.1.2023-.pdf

Gejo-García, J., Reschke, J., Gallego-García, S., & García-García, M. (2022). Development of a System Dynamics Simulation for Assessing Manufacturing Systems Based on the Digital Twin Concept. *Applied Sciences (Switzerland)*, *12*(4). https://doi.org/10.3390/app12042095

Georgious, R., Refaat, R., Garcia, J., & Daoud, A. A. (2021). Review on energy storage systems in microgrids. In *Electronics (Switzerland)* (Vol. 10, Issue 17). MDPI. https://doi.org/10.3390/electronics10172134

Giannelis, A., Symeonidou, I., Tzetzis, D., Kaisarlis, G., & Kyratsis, P. (2017). Laser scanning and CAD conversion accuracy correction of a highly curved engineering component using a precision tactile measuring system. *MATEC Web of Conferences*, *112*. https://doi.org/10.1051/matecconf/201711205009

Gibson, I., Rosen, D. W., & Stucker, B. (2010). Sheet Lamination Processes. In *Additive Manufacturing Technologies*. https://doi.org/10.1007/978-1-4419-1120-9_8

Grieves, M. (2014). Digital Twin : Manufacturing Excellence through Virtual Factory Replication. *White Paper*, *March*.

Grobelna, I., & Karatkevich, A. (2021). Challenges in application of petri nets in manufacturing systems. In *Electronics (Switzerland)* (Vol. 10, Issue 18). https://doi.org/10.3390/electronics10182305

Hacksteiner, M., Peherstorfer, H., & Bleicher, F. (2018). Energy efficiency of state-of-the-art grinding processes. *Procedia Manufacturing*, *21*. https://doi.org/10.1016/j.promfg.2018.02.176

Hart, G. W. (1992). Nonintrusive Appliance Load Monitoring. *Proceedings of the IEEE*, *80*(12). https://doi.org/10.1109/5.192069

Hasan, A. S. M. M., & Trianni, A. (2020). A review of energy management assessment models for industrial energy efficiency. In *Energies* (Vol. 13, Issue 21). https://doi.org/10.3390/en13215713

He, B., & Bai, K. J. (2021). Digital twin-based sustainable intelligent manufacturing: a review. *Advances in Manufacturing*, *9*(1). https://doi.org/10.1007/s40436-020-00302-5

Hu, B., Xu, S., Wang, R. Z., Liu, H., Han, L., Zhang, Z., & Li, H. (2019). Investigation on advanced heat pump systems with improved energy efficiency. *Energy Conversion and Management*, *192*, 161–170. https://doi.org/10.1016/j.enconman.2019.04.031

Huan, C., Li, S., Wang, F., Liu, L., Zhao, Y., Wang, Z., & Tao, P. (2019). Performance analysis of a combined solar-assisted heat pump heating system in Xi’an, China. *Energies*, *12*(13). https://doi.org/10.3390/en12132515

Hurmekoski, E., & Hetemäki, L. (2013). Studying the future of the forest sector: Review and implications for long-term outlook studies. In *Forest Policy and Economics* (Vol. 34). https://doi.org/10.1016/j.forpol.2013.05.005

Introduction to the Theory of Flow Machines. (1966). In *Introduction to the Theory of Flow Machines*. https://doi.org/10.1016/c2013-0-05426-6

iso.org. (2018). Iso 50001 Energy Management System. *When Recognition Matters WHITEPAPER*.

IEA (2021), *Global Energy Review 2021*, IEA, Paris https://www.iea.org/reports/global-energy-review-2021, License: CC BY 4.0

IEA. (2021). *Renewables 2021.* Paris: IEA. Retrieved 2022, from https://www.iea.org/reports/renewables-2021,

IEA. (2022). *Renewable Electricity.* Paris: IEA. Retrieved 2022, from https://www.iea.org/reports/renewable-electricity

IMF. (2022). *IMF data*. Retrieved from International Monetary Fund: https://www.imf.org/en/Data

Jahangirian, M., Eldabi, T., Naseer, A., Stergioulas, L. K., & Young, T. (2010). Simulation in manufacturing and business: A review. *European Journal of Operational Research*, *203*(1). https://doi.org/10.1016/j.ejor.2009.06.004

Kabir, E., Kumar, P., Kumar, S., Adelodun, A. A., & Kim, K. H. (2018). Solar energy: Potential and future prospects. In *Renewable and Sustainable Energy Reviews* (Vol. 82, pp. 894–900). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.09.094

Khaswala, Z. N., & Irani, S. A. (2001). Value Network Mapping (VNM): Visualization and Analysis of Multiple Flows in Value Stream Maps. *Proceedings of the Lean Management Solutions Conference*, *614*.

Le, K. X., Huang, M. J., Wilson, C., Shah, N. N., & Hewitt, N. J. (2020). Tariff-based load shifting for domestic cascade heat pump with enhanced system energy efficiency and reduced wind power curtailment. *Applied Energy*, *257*. https://doi.org/10.1016/j.apenergy.2019.113976

Li, C. (2018). Comparative performance analysis of grid-connected PV power systems with different PV technologies in the hot summer and cold winter zone. *International Journal of Photoenergy*, *2018*. https://doi.org/10.1155/2018/8307563

Liang, X., Kankare, V., Hyyppä, J., Wang, Y., Kukko, A., Haggrén, H., Yu, X., Kaartinen, H., Jaakkola, A., Guan, F., Holopainen, M., & Vastaranta, M. (2016). Terrestrial laser scanning in forest inventories. *ISPRS Journal of Photogrammetry and Remote Sensing*, *115*. https://doi.org/10.1016/j.isprsjprs.2016.01.006

Lin, Y.; Bu, Z.; Yang, W.; Zhang, H.; Francis, V.; Li, C.-Q. A Review on the Research and Development of Solar-Assisted Heat Pump for Buildings in China. Buildings 2022, 12, 1435. https:// doi.org/10.3390/buildings12091435

Lipiäinen, S., & Vakkilainen, E. (2021). Role of the Finnish forest industry in mitigating global change: energy use and greenhouse gas emissions towards 2035. *Mitigation and Adaptation Strategies for Global Change*, *26*(2). https://doi.org/10.1007/s11027-021-09946-5

Luke. (2022, November 17). *Total wood consumption 2021*. Retrieved 2022, from Luke - Natural Resource Institute Finland: https://www.luke.fi/en/statistics/total-wood-consumption/total-wood-consumption-2021

Manouchehri, F., Nookabadi, A. S., & Kadivar, M. (2020). Production routing in perishable and quality degradable supply chains. *Heliyon*, *6*(2). https://doi.org/10.1016/j.heliyon.2020.e03376

Manufacturing processes reference guide. (1994). *Choice Reviews Online*, *32*(04). https://doi.org/10.5860/choice.32-2157

Mao, Q., & Chen, Y. (2017). Experimental investigation of thermal performance of a ground source heat pump system for spring season. *Energy and Buildings*, *152*. https://doi.org/10.1016/j.enbuild.2017.07.067

Micieta, B., Markovic, J., & Binasova, V. (2016). Advances in sustainable energy efficient manufacturing system. *MM Science Journal*, *2016-June*. https://doi.org/10.17973/MMSJ.2016_06_201615

Mikola, A., & Kõiv, T.-A. (2014). The Efficiency Analysis of the Exhaust Air Heat Pump System. *Engineering*, *06*(13). https://doi.org/10.4236/eng.2014.613093

Milgram, P., & Kishino, F. (1994). Taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, *E77-D*(12).

Mudgal, D., Pagone, E., Alkhunani, R. A., & Salonitis, K. (2021). Life-cycle-Assessment of Cast Stone Manufacturing: A Case Study. *Procedia CIRP*, *104*. https://doi.org/10.1016/j.procir.2021.11.105

Müller, E., Stock, T., & Schillig, R. (2014a). A method to generate energy value-streams in production and logistics in respect of time- and energy-consumption. *Production Engineering*, *8*(1–2), 243–251. https://doi.org/10.1007/s11740-013-0516-9

Müller, E., Stock, T., & Schillig, R. (2014b). A method to generate energy value-streams in production and logistics in respect of time- and energy-consumption. *Production Engineering*, *8*(1–2). https://doi.org/10.1007/s11740-013-0516-9

Muñoz-Saavedra, L., Miró-Amarante, L., & Domínguez-Morales, M. (2020). Augmented and virtual reality evolution and future tendency. *Applied Sciences (Switzerland)*, *10*(1). https://doi.org/10.3390/app10010322

Muntean, M., Dănăiaţă, D., Hurbean, L., & Jude, C. (2021). A business intelligence & analytics framework for clean and affordable energy data analysis. *Sustainability (Switzerland)*, *13*(2). https://doi.org/10.3390/su13020638

Nabitz, L., & Hirzel, S. (2019). Transposing The Requirements of the Energy Efficiency Directive on Mandatory Energy Audits for Large Companies: A Policy-Cycle-based review of the National Implementation in the EU-28 Member States. *Energy Policy*. https://doi.org/10.1016/j.enpol.2017.12.016

Negahban, A., & Smith, J. S. (2014). Simulation for manufacturing system design and operation: Literature review and analysis. In *Journal of Manufacturing Systems* (Vol. 33, Issue 2). https://doi.org/10.1016/j.jmsy.2013.12.007

Nouiri, M., Bekrar, A., & Trentesaux, D. (2020). An energy-efficient scheduling and rescheduling method for production and logistics systems†. *International Journal of Production Research*, *58*(11), 3263–3283. https://doi.org/10.1080/00207543.2019.1660826

Nokian Capacitors. (2004). Power factor correction. Tampere, Finland. Retrieved 2022, from http://www.nokiancapacitors.ru/documents/theory/EN-TH01-11_2004-Power_Factor_Correction.pdf

Official Statistics of Finland (OSF). (2020). *Energy supply and consumption.* Retrieved 2022, from http://www.stat.fi/til/ehk/2020/04/ehk_2020_04_2021-04-16_tie_001_en.html

Ohno, T., & Bodek, N. (2019). Toyota Production System: Beyond Large-Scale Production. In *Toyota Production System: Beyond Large-Scale Production*. https://doi.org/10.4324/9780429273018

Ortiz-Sanz, J., Gil-Docampo, M., Rego-Sanmartín, T., Arza-García, M., & Tucci, G. (2021). A PBeL for training non-experts in mobile-based photogrammetry and accurate 3-D recording of small-size/non-complex objects. *Measurement: Journal of the International Measurement Confederation*, *178*. https://doi.org/10.1016/j.measurement.2021.109338

Özel, T., & Karpat, Y. (2005). Predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks. *International Journal of Machine Tools and Manufacture*, *45*(4–5). https://doi.org/10.1016/j.ijmachtools.2004.09.007

Pang, T. Y., Pelaez Restrepo, J. D., Cheng, C. T., Yasin, A., Lim, H., & Miletic, M. (2021). Developing a digital twin and digital thread framework for an ‘industry 4.0’ shipyard. *Applied Sciences (Switzerland)*, *11*(3). https://doi.org/10.3390/app11031097

Psimopoulos, E., Bee, E., Widén, J., & Bales, C. (2019). Techno-economic analysis of control algorithms for an exhaust air heat pump system for detached houses coupled to a photovoltaic system. *Applied Energy*, *249*, 355–367. https://doi.org/10.1016/j.apenergy.2019.04.080

Pylsy, P., & Kurnitski, J. (2021). Measured performance of exhaust air heat pumps in Finnish apartment buildings. *E3S Web of Conferences*, *246*. https://doi.org/10.1051/e3sconf/202124606001

Puucomp. (2022). Retrieved from https://www.puucomp.com/fi/

Puucomp. (2022). *Puucomp premium*. Retrieved from https://www.puucomp.com/en/puucomp-premium

Statista. (2022). *Manufacture of Wood - Finland*. Retrieved from Statista: https://www.statista.com/outlook/io/manufacturing/manufacture-of-wood/finland

Qamar, N., Malik, T. N., Qamar, F., Ali, M., & Naeem, M. (2021). Energy hub: modeling, control, and optimization. In *Renewable Energy Systems*. https://doi.org/10.1016/b978-0-12-820004-9.00018-8

Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L., & Nee, A. Y. C. (2021). Enabling technologies and tools for digital twin. *Journal of Manufacturing Systems*, *58*, 3–21. https://doi.org/10.1016/j.jmsy.2019.10.001

Rafsanjani, H. N., & Nabizadeh, A. H. (2021). Towards digital architecture, engineering, and construction (AEC) industry through virtual design and construction (VDC) and digital twin. *Energy and Built Environment*. https://doi.org/10.1016/j.enbenv.2021.10.004

Rahman, A. Z. M. S. (2016). Solid State Luminescent Materials: Applications. In *Reference Module in Materials Science and Materials Engineering*. https://doi.org/10.1016/b978-0-12-803581-8.04078-9

Rödger, J. M., Beier, J., Schönemann, M., Schulze, C., Thiede, S., Bey, N., Herrmann, C., & Hauschild, M. Z. (2021). Combining Life Cycle Assessment and Manufacturing System Simulation: Evaluating Dynamic Impacts from Renewable Energy Supply on Product-Specific Environmental Footprints. *International Journal of Precision Engineering and Manufacturing - Green Technology*, *8*(3), 1007–1026. https://doi.org/10.1007/s40684-020-00229-z

Saidur, R., Rahim, N. A., Islam, M. R., & Solangi, K. H. (2011). Environmental impact of wind energy. In *Renewable and Sustainable Energy Reviews* (Vol. 15, Issue 5, pp. 2423–2430). Elsevier Ltd. https://doi.org/10.1016/j.rser.2011.02.024

Sampaio, P. G. V., & González, M. O. A. (2017). Photovoltaic solar energy: Conceptual framework. In *Renewable and Sustainable Energy Reviews* (Vol. 74). https://doi.org/10.1016/j.rser.2017.02.081

Saunders, M., Lewis, P., & Thornhill, A. (2007). Research methods for business students (4TH Edition), Financial Times Prentice Hall. London.UK Schuler,. *Journal of Economic Perspectives*, *16*(4).

Saunders, M., Lewis, P., & Thornhill, A. (2019). Understanding Reseach Philisophy and Approaches to Theory Development. In *Research Methods for Business Students*.

Schillig, R., Stock, T., & Müller, E. (2015). Energy value-stream mapping a method to visualize waste of time and energy. *IFIP Advances in Information and Communication Technology*, *459*. https://doi.org/10.1007/978-3-319-22756-6_74

Sepasgozar, S. M. E. (2020). Digital twin and web-based virtual gaming technologies for online education: A case of construction management and engineering. *Applied Sciences (Switzerland)*, *10*(13). https://doi.org/10.3390/app10134678

Shan, J., Hu, Z., Tao, P., Wang, L., Zhang, S., & Ji, S. (2020). Toward a unified theoretical framework for photogrammetry. *Geo-Spatial Information Science*, *23*(1). https://doi.org/10.1080/10095020.2020.1730712

Shirani, A., Merzkirch, A., Roesler, J., Leyer, S., Scholzen, F., & Maas, S. (2021). Field monitoring data on a residential exhaust air heat pump system (air-to-air heat pump). *Data in Brief*, *38*. https://doi.org/10.1016/j.dib.2021.107386

Stark, R., Kind, S., & Neumeyer, S. (2017). Innovations in digital modelling for next generation manufacturing system design. *CIRP Annals - Manufacturing Technology*, *66*(1). https://doi.org/10.1016/j.cirp.2017.04.045

Tao, F., Liu, W., Zhang, M., Hu, T., Qi, Q., Zhang, H., Sui, F., Wang, T., Xu, H., Huang, Z., Ma, X., Zhang, L., Cheng, J., Yao, N., Yi, W., Zhu, K., Zhang, X., Meng, F., Jin, X., … Luo, Y. (2019). Five-dimension digital twin model and its ten applications. *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS*, *25*(1). https://doi.org/10.13196/j.cims.2019.01.001

Todorovic, M. (2012). Large scale residential/municipal RES integrated refurbishment construction and HVAC systems engineering R&D needs. *ASHRAE Transactions*, *118*(PART 1).

Truong, N. B., Sun, K., Lee, G. M., & Guo, Y. (2020). GDPR-Compliant Personal Data Management: A Blockchain-Based Solution. *IEEE Transactions on Information Forensics and Security*, *15*. https://doi.org/10.1109/TIFS.2019.2948287

Umer, R., Bickerton, S., & Fernyhough, A. (2007). Characterising wood fibre mats as reinforcements for liquid composite moulding processes. *Composites Part A: Applied Science and Manufacturing*, *38*(2). https://doi.org/10.1016/j.compositesa.2006.03.003

Urchueguía, J. F., Zacarés, M., Corberán, J. M., Montero, Á., Martos, J., & Witte, H. (2008). Comparison between the energy performance of a ground coupled water to water heat pump system and an air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast. *Energy Conversion and Management*, *49*(10). https://doi.org/10.1016/j.enconman.2008.03.001

Verma, N., & Sharma, V. (2016). Energy value stream mapping a tool to develop green manufacturing. *Procedia Engineering*, *149*. https://doi.org/10.1016/j.proeng.2016.06.701

Verma, N., Sharma, V., & Badar, M. A. (2021). Entropy-Based Lean, Energy and Six Sigma Approach to Achieve Sustainability in Manufacturing System. *Arabian Journal for Science and Engineering*, *46*(8). https://doi.org/10.1007/s13369-021-05826-x

Wang, H., Jiang, Z., Wang, Y., Zhang, H., & Wang, Y. (2018). A two-stage optimization method for energy-saving flexible job-shop scheduling based on energy dynamic characterization. *Journal of Cleaner Production*, *188*. https://doi.org/10.1016/j.jclepro.2018.03.254

Wang, J., Fei, Z., Chang, Q., & Li, S. (2019). Energy saving operation of manufacturing system based on dynamic adaptive fuzzy reasoning petri net. *Energies*, *12*(11). https://doi.org/10.3390/en12112216

Wang, S., Lu, X., Li, X. X., & Li, W. D. (2015). A systematic approach of process planning and scheduling optimization for sustainable machining. *Journal of Cleaner Production*, *87*(1). https://doi.org/10.1016/j.jclepro.2014.10.008

Wang, Z., Luther, M. B., Amirkhani, M., Liu, C., & Horan, P. (2021). State of the art on heat pumps for residential buildings. *Buildings*, *11*(8). https://doi.org/10.3390/buildings11080350

Weyant, E. (2022). Research Design: Qualitative, Quantitative, and Mixed Methods Approaches, 5th Edition. *Journal of Electronic Resources in Medical Libraries*, *19*(1–2). https://doi.org/10.1080/15424065.2022.2046231

Xu, T., You, J., Li, H., & Shao, L. (2020). Energy efficiency evaluation based on data envelopment analysis: A literature review. In *Energies* (Vol. 13, Issue 14). MDPI AG. https://doi.org/10.3390/en13143548

Yan, J., Li, L., Zhao, F., Zhang, F., & Zhao, Q. (2016). A multi-level optimization approach for energy-efficient flexible flow shop scheduling. *Journal of Cleaner Production*, *137*. https://doi.org/10.1016/j.jclepro.2016.06.161

Zhang, Z., Tang, R., Peng, T., Tao, L., & Jia, S. (2016). A method for minimizing the energy consumption of machining system: integration of process planning and scheduling. *Journal of Cleaner Production*, *137*. https://doi.org/10.1016/j.jclepro.2016.03.101