TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

TALLINNA TEHNIKAÜLIKOOL

PRODUCTION MONITORING SYSTEM FOR SMALL AND MEDIUM-SIZED ENTERPRISES

TOOTMISE JÄLGIMISSÜSTEEM VÄIKESE JA KESKMISE SUURUSEGA ETTEVÕTETE JAOKS

MASTER THESIS

Student:	Fred-Georg Pääro
Student code:	204815MAHM
Supervisor:	Kristjan Pütsep, Lecturer
Co-supervisor:	Eduard Petlenkov, Tenured Full Professor

Tallinn 2022

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

“18” May 2022

Author: Fred-Georg Pääro
/ signature /

Thesis is in accordance with terms and requirements

“18” May 2022 .

Supervisor: Kristjan Pütsep, Eduard Petlenkov
/ signature /

Accepted for defence

“.......”....................2022 .

Chairman of theses defence commission: ....
/ name and signature /

Non-exclusive Licence for Publication and Reproduction of GraduationThesis[1]

I, Fred-Georg Pääro (date of birth: 21/07/1998)

hereby

1. grant Tallinn University of Technology (TalTech) a non-exclusive license for my thesis

"Production Monitoring System for Small and Medium-sized Enterprises",

supervised by

Kristjan Pütsep – Lecturer, Tallinn University of Technology,

Eduard Petlenkov – Tenured Full Professor, Tallinn University of Technology,

1.1 reproduced for the purposes of preservation and electronic publication, incl. to be entered in the digital collection of TalTech library until the expiry of the term of copyright;

1.2 published via the web of TalTech, incl. to be entered in the digital collection of TalTech library until the expiry of the term of copyright.

1.3 I am aware that the author also retains the rights specified in clause 1 of this license.

2. I confirm that granting the non-exclusive license does not infringe third persons' intellectual property rights, the rights arising from the Personal Data Protection Act or rights arising from other legislation.

---

[1] *Non-exclusive Licence for Publication and Reproduction of Graduation Thesis is not valid during the validity period of restriction on access, except the university`s right to reproduce the thesis only for preservation purposes.*

______________ (*signature*)

18. May 2022 (*date*)

Department of Electrical Power Engineering and Mechatronics

THESIS TASK

Student:	Fred-Georg Pääro, 204815MAHM
Study programme:	MAHM , Mechatronics
Supervisor:	Lecturer, Kristjan Pütsep, +372 6203305
Co-supervisor:	Tenured Full Professor, Eduard Petlenkov, +372 6202104
Consultants:	Tarmo Pääro, CEO, VR-Koda OÜ

Thesis topic:

(In English)	Production Monitoring System for Small and Medium-sized Enterprises
(In Estonian)	Tootmise jälgimissüsteem väikese ja keskmise suurusega ettevõtete jaoks

Thesis main objectives:

1. Develop a reliable and autonomous production monitoring system for small and medium-sized enterprises covering:
    a. Production monitoring
    b. Environment and facility monitoring
    c. Maintenance management
    d. Production prediction
2. Implement new input acquiring methods (current sensor)
3. Develop smart algorithms for input processing and system execution
4. Implementation of new visualization platform
5. Predict production output of the company with Machine Learning (ML)
6. Implement developed system practically

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Research	31. Oct
2.	Existing data analysis for production prediction development	30. Nov
3.	Development of algorithms for PLC, data storing and visualization	31. Jan
4.	Setting up all the hardware, and cabling on site	28. Feb
5.	Testing and verifying on site	31. Mar
6.	Thesis compiled with all the material	30. Apr
7.	Thesis defense	01. Jun

Language: English **Deadline for submission of thesis:** "18" May 2022

Student:	Fred-Georg Pääro	.... /signature/	"18" May 2022
Supervisor:	Kristjan Pütsep	.... /signature/	"18" May 2022
Co-supervisor:	Eduard Petlenkov	.... /signature/	"18" May 2022
Program Director:	Anton Rassõlkin	.... /signature/	"....".......2022

Terms of thesis closed defence and/or thesis restricted access conditions to be formulated on the reverse side

ABSTRACT

This thesis aims to develop and practically test a Production Monitoring System (PMS) covering: production monitoring, environment, and facility monitoring, maintenance management, and production prediction. The work presented is a further development of a bachelor's thesis [2]. However, the concept of PMS is further refined, supplemented, and handled from the perspective of the system as a product in the future. The system is designed and developed in a standardized way. It aims to provide information from production and its relevant areas as automatically as possible while still guaranteeing reliability and a convenient user experience.

The thesis's main body is divided into four chapters. The first chapter focuses on analyzing existing systems and their concepts to validate the need for such development. As a result of the analysis, aims are set for the system development. The second chapter targets creating the PMS concept design to form the basis for technical development. The chapter sets the system's requirements, functionalities, structure, and principles. The third chapter concentrates on system hardware and software components, their selection, and installation, including their financial evaluation. The last chapter provides an overview of the control system development, including all the monitoring and execution algorithms. On top of that, the chapter incorporates the user interface- and reporting system development.

The result of this thesis is a complete PMS designed for small and medium-sized enterprises. It solves some shortcomings within existing systems, which mainly are cost, hardware reliability, and required user interaction. The system complies with the set design requirements being a one-time investment with reliable hardware, low management requirements, and autonomous operating principles. In order to test the system in real-life conditions, the system was set up in a footwear industry company. Thanks to the standardized system design and development approach, the overall solution is a decisive step closer to being an actual product-type solution.

Keywords: Production monitoring, maintenance management, production prediction, monitoring algorithms, current transformer, PLC, HMI, reporting, master's thesis.

CONTENTS

PREFACE

The current work is a continuation of development started during bachelor thesis, which targeted creating an industrial work time monitoring system in the production company VR-Koda OÜ. The company established 30 years ago produces mountain ski boots, which require various types of production machinery that are mainly manually operated. Due to the high degree of manual labor, there was an apparent need for a work time monitoring system to capture the production efficiency, machines' utilization, and effort allocated by personnel. As the previously tested systems in the market did not meet the company's needs, a tailor-made system was developed.

Advances in the production monitoring field within the past two years have made this topic much more active with broader coverage in research and solutions on the market. However, there is still an absence of systems with similar features and fundamentals on which the system was built during the bachelor thesis. Therefore, this thesis continues the development on the same topic, however, from a perspective of a solution as a product to be applicable in other productions in the future. Thus, the development was conducted much more systematically, aiming for standardization and universality. Moreover, the overall system concept was refined, resulting in a production monitoring system (PMS) covering a wider area related to the company's operations. The physical system itself is installed at the same company, utilizing the existing base structure of the previous system. Furthermore, thanks to the system available from bachelor thesis, the development and testing have been continuously ongoing for about two and half years until today.

The completion of the work and development of the system took place under the supervision of Kristjan Pütsep and Eduard Petlenkov from Tallinn University of Technology. Kristjan Pütsep is a lecturer at the Department of Electrical Power Engineering and Mechatronics, and Eduard Petlenkov is a tenured full professor at the Centre of Intelligent Systems. Despite the long development and testing period, many difficulties were faced during the conductance of this thesis due to pandemics and long delivery times. Therefore, I would like to thank Beckhoff Automation OÜ, Klinkmann Eesti AS, and VR-Koda OÜ for the advice and pleasant and understanding cooperation received during the various stages of compiling the work.

LIST OF ABBREVATIONS

ADS	Automation Device Specification protocol
AI	Artificial Intelligence
AMQP	Advanced Message Queuing Protocol
ANN	Artificial Neural Network
CoAP	Constrained Application Protocol
CPU	Central Processing Unit
EMC	Electromagnetic Compatibility
ERP	Enterprise Resource Planning
GVL	Global Variable List
HMI	Human Machine Interface
HTTP	Hypertext Transfer Protocol
IIoT	Industrial Internet of Things
I/O	Input/Output
IoT	Internet of Things
IP	Internet Protocol
KPI	Key Performance Indicators
LAN	Local Area Network
MES	Manufacturing Execution System
ML	Machine Learning
MLP	Multi-Layer Perceptron
MQTT	MQ Telemetry Transport protocol
OEE	Overall Equipment Efficiency
ONNX	Open Neural Network Exchange
OPC UA	Open Platform Communications United Architecture
OSI	Open Systems Interconnection
PLC	Programmable Logic Controller
PMS	Production Monitoring System

RFID	Radio-Frequency Identification
RTD	Resistance Temperature Detector
RTOS	Real-Time Operating System
SaaS	System as a Service
SCADA	Supervisory Control and Data Acquisition
SME	Small and Medium-sized Enterprises
SVM	Support Vector Machine
TCP	Transmission Control Protocol
TTL	Transistor-Transistor Logic
UDP	User Datagram Protocol
WAN	Wide Area Network
WMSN	Wireless Mesh Sensor Network
WSN	Wireless Sensor Network
XMPP	Extensible Messaging and Presence Protocol

LIST OF FIGURES

1. INTRODUCTION

Improvements in technology, especially in industrial automation, have significantly increased productivity, quality, and safety in industrial applications. Industry 4.0 relies on nine pillars, of which one of the most important is "Big Data and Analytics." Data from different sources regarding production equipment, enterprise, and customer management is collected and used to support real-time decision-making and monitoring [1]. Before being able to utilize the possibilities of data-driven decision-making in production, a medium that provides necessary information has to be created. Production Monitoring System (PMS) provides real-time and historical information from the production floor to management.

The applicability of PMS solutions is highly varying depending on the field of activity. In big production companies with a high degree of automation, most processes are already digitalized and, therefore, easily monitorable. Besides those, various fields cannot be automated to such a level either due to financial reasons or the nature of the production. This applies especially to smaller companies or those with varying and unstandardized equipment. Despite that, the need for an overview of current production flow, statistics, and historical data exists.

Most PMS solutions on the market are sold as services on a monthly basis. They are developed to be universal products that can be easily installed on production equipment. Those types of systems may cover the needs of some companies. However, there are various fields and conditions where they fall short. The main technical aspects for this are reliability issues in harsher conditions with often used wireless communication, limited integration with different equipment, and required user action. On top of this, utilization of such systems due to usually service-type products is expensive. This creates a need for alternative solutions that cover the existing shortcomings for some companies.

The Current thesis handles the problem of production monitoring in Small and Medium-sized Enterprises (SMEs) from a different perspective. The approach differs from the bottom as the fundamentals are built on industrial automation, including hardware and system control. The concept was developed during bachelor thesis [2] and will be further developed, optimized, and expanded during this master’s thesis. The system design principles remain unchanged, which was to develop easily manageable, reliable, and flexible PMS, charged from customers’ site as a one-time investment. However, the overall objective has been supplemented, and the master’s thesis examines problems and solutions much more broadly.

As a result of this thesis, a complete product of PMS is developed, suitable for SMEs ranging from tens of machines to a few hundred. A more unified system could be assembled thanks to the recent improvements in industrial automation products, hardware, and software. The central objective is to provide more data from the production floor more intelligently while still aiming for high reliability and cost-effective solution. New functionalities such as environment and facility monitoring and maintenance management for equipment servicing will be deployed to the system. Moreover, the preparations and first developments for predicting the production outcome in the future will be made. The developed system will be implemented in a footwear industry company, which serves as a good testing platform due to the large amount of manual labor and various equipment used.

The thesis’s main body is divided into four chapters. The first chapter concentrates on a literature review to thoroughly analyze different concepts of PMS and their functionalities. In the second chapter, the developed PMS concept is formed together with integrated functionalities to create a logical basis for technical development. The third chapter discusses system hardware and software components on all levels, including the equipment from the previous PMS version. However, the main effort is put into new input acquiring hardware. The fourth and final chapter includes a discussion of the whole control system development covering algorithms- and user interface development.

2. LITERATURE REVIEW

2.1 The concepts of PMS solutions

2.1.1 PMS concept description

The constant evolution of production technologies and rising demand for high-quality products on the market have created a need for manufacturing companies to precisely monitor their activities. In today's production, efficient planning and managing of resources and processes can be achieved using digital area tools. One of them is the PMS, which helps enterprises automatically acquire relevant data from production processes with improved efficiency and consistency compared to manual data collection [3]. The parameters of interest for monitoring are widely varying depending on the production type and desired outcome. The main areas for monitoring and the relationships between them proposed in the research paper [3] are visualized in the following Figure 2.1.

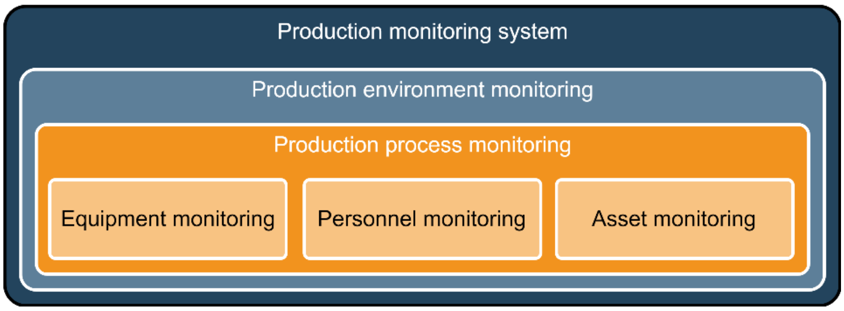


Figure 2.1. PMS monitoring areas

The employment of PMS concepts depends mainly on the size and type of the enterprise. Another critical factor is manufacturing equipment, which dictates the integration possibilities according to their construction and overall standardization across the production floor. The available PMS solutions can be divided into two categories based on their logical concept – centralized- and decentralized systems. However, as the needs vary greatly, there are relatively thin lines between them, and the personalization depending on the specific company is a significant factor in the systems.

Another important matter regarding the classification of PMS solutions is that it could be seen as a subset of the Manufacturing Execution System (MES), which offers functions like data collection, resource status, production performance analysis, and others. However, machinery monitoring, which is one of the main functions of PMS, is not the primary goal of the majority of MES solutions. The reason is that the initial idea of MES was to provide higher level, mainly Enterprise Resource Planning (ERP), with the required production status data from the workshop [4]. Due to this, a distinction has to be made between PMS and MES. As the objective is to find solutions for production monitoring involving physical means (control hardware), the MES software is not covered and classified during background review. However, the possibility of influence through integration should be acknowledged in the future.

2.1.2 Decentralized systems

The most comprehensive coverage in research papers and products available on the market has a topology where data from equipment and environment is gathered using edge devices; thus, they can be referred to as decentralized. Those systems are often built on IoT or IIoT (Internet of Things or Industrial Internet of Things) [4-8]. The characteristic features are the presence of a computing device attached to each production machine or workplace, which is responsible for initial data processing and transmission to a central web-based or local server. Wireless Sensor Networks (WSN) and wireless communication are highly favored in those systems.

Approaches proposed in [4-8] are used for slightly different purposes (e.g., production monitoring, production environment monitoring, etc.), but they all leverage similar concepts in terms of system structure. A thorough discussion and the conceptual design of a decentralized type of PMS suitable for SMEs are given in [4]. The possibility of expanding the system in terms of monitored equipment and functionality is emphasized. The edge computing devices used for data collection and propagation to upper levels of the system are small not-industrial grade microcontrollers equipped with necessary sensors.

In [5], data is recorded locally through mediums such as current transformer sensor, RFID, and barcode. Then, information is processed and forwarded to the shop floor application for analysis. IoT-based production output monitoring system in [6] proposes a similar concept. However, the data is sent to the cloud service for storing and analysis. Wireless Mesh Sensor Network (WMSN) is introduced in [7] to widen the coverage area of the PMS and simplify the installation. The WMSN is realized by placing sensor nodes and one sink node on each production line. The sink node is responsible for data querying from other nodes and supplying it to the monitoring center, where personnel can access it. A production environment monitoring solution is compiled in [8], where data is collected using similar means. However, the transmission to the central database is done using publish/subscribe method with the MQTT protocol.

As mentioned, the solutions available on the market primarily utilize the benefits of IoT. The structure of offered systems could be generally classified as decentralized or edge device systems. They are commonly practicing System as a Service (SaaS) business model. Systems are created following a principle of flexibility by allowing expansion in the number of equipment and functionalities. The most popular PMS providers from Estonia are Evocon [9] and Global Reader [10]. The most notable classical PMS solutions in the world market are MachineMetrics [11], Matics [12], and Monitor-Box [13].

2.1.3 Centralized systems

The second and less represented type of monitoring system has a more centralized structure. Often, the input acquiring layer has only sensor systems, or it is realized on top of existing devices (e.g., PLC – Programmable Logic Controller). The data is propagated directly from existing devices to the central processing unit or server [14-16]. Those systems are commonly more sophisticated in their structure and used technologies. The complex structure is caused because elementary solutions do not meet the needs, or integration with existing devices requires additional modules in the form of hardware and software. Those systems are often custom-built and commonly feature niche aspects to suit specific companies. However, some of the previously mentioned decentralized types of PMS providers offer ways to integrate existing hardware, e.g., PLC, to connect directly to their application layer [9, 11, 13].

The PMS concepts created in [14-16] could be classified as centralized based on principle structure. The system developed in [14] could be used as a universal wireframe for solving the monitoring task in factories with process control equipment available on-site. The proposed solution takes advantage of PLCs by utilizing the naturally existing process control data for monitoring purposes. The real-time data is sent to the cloud server via MQTT protocol, where it will be further processed and stored for monitoring over a web-server-based platform. A complex problem of manual production monitoring is solved in [15] by developing an advanced camera-based cyber-physical system for assembly operations. Apart from pure monitoring, the system is intended to guide the employee during assembly and check the completeness of procedures. The data from the workplace is acquired through a camera and operator inputs on an industrial monitor. Information is collected to the central computing station, from where it will be distributed to assembly as feedback and to managers as process statistics.

The security monitoring aspects are covered in [16] with a system running on soft PLC. The status of equipment and environment is captured with sensors connected to a physical PLC module that transmits the signals to the upper layer server for processing and visualization for users on a remote platform. Pure industrial automation-based PMS is designed in [2]. The system is divided into three different levels, similarly to the classical automation pyramid (Figure 2.2). The first level is input acquiring, where all sorts of sensors are implemented to gather relevant signals from production equipment. The second level is the control and logic level of the system, where industrial PLC is used for data processing and system execution. The third and highest level is used for real-time visualization, reporting, and historicization.

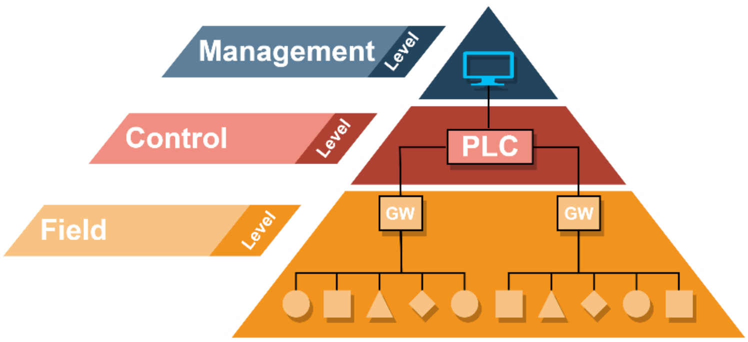


Figure 2.2. PLC-based PMS [2]

2.2 Hardware and communication principles

2.2.1 Hardware

The hardware requirements in industrial applications are a rather sensitive topic tied with numerous standards and policies. The strict requirements for process-related hardware are mainly set to protect people from hazardous occasions and minimize the chances of failure resulting in material and financial loss. By nature, PMS is a system, which interacts with production machinery in a so-called "read-only" form to collect process parameters and production information. Hence, the requirements are less strict as far as the system itself could not cause any danger to humans or the reliability of service is not violated.

The transformation of IoT into IIoT, which still takes advantage of all the key features, brings more sophisticated systems. The main differences between regular consumer-grade IoT devices and those applicable in the industrial field are system complexity, communication protocols and medium, amount of data, and evaluation factor [17]. IoT states cost, flexibility, and energy efficiency in the scope of hardware as the main characteristics. Devices used in decentralized PMS are mainly small single-board computers like Raspberry PI and single-board microcontrollers such as Arduino. Some of the key features to be considered when implementing PMS functionalities on these kinds of devices are communication interfaces, support of analog inputs (analog-to-digital converter), and the presence of a real-time operating system (RTOS) [4]. Thanks to the rapid evolution and broader implementation of IoT solutions, companies producing small embedded platforms are constantly improving existing platforms and releasing new ones to the market.

The decentralized type of systems presented in papers are mainly applying microcontrollers and microcomputers available on the market. The use of such platforms often involves the usage of similar level sensors in terms of reliability and cost. For example, an automatic production monitoring system developed in [5] uses HMI (Human Machine Interface) powered by Raspberry PI at each machine. Along with visualization, Raspberry serves as a medium for data collection and transmission. The sensor level attached to the platform is equipped with an RFID reader (operator card recognition), a barcode reader (order sheet recognition), and a current transformer (machine work time detection). Unlike most PMSs, the concept introduces actuation to the production through a relay to disable machine operation if the operator has not filled necessary actions. The wireless mesh sensor network-based approach in [7] uses similar hardware in nodes serving different purposes. The NRF905 transceiver chip is used, which is designed for industrial ISM band.

One of the most used platforms for PMSs in research papers is Arduino Uno. The production output monitoring system built for a plastic packaging manufacturing process integrates an Arduino board with an industrial encoder to measure the length of produced plastic film. The output of the conventional industrial counter is connected to a MAX485 module to convert RS485 to Transistor-Transistor Logic (TTL). TTL is used as an input for Arduino, and the processed data is transmitted to the cloud through the ESP8266 Wi-Fi module [6]. Similar components have been selected for production environment monitoring to see the effect on the performance in [8]. The difference comes at the sensor level, where non-industrial sensors are used.

The decentralized type of solutions available on the market are usually built on similar hardware as the overall system concept relies on the same principles. However, as the hardware is a competitive advantage of the system, companies in this field are not publishing its details. On behalf of required hardware, Evocon company brings out Evocon's IIoT device (production signals logging), sensor or relay, and a display device unless suitable hardware for integration is already available on-site [9]. Similar hardware is required for the Global Reader-provided system [10].

MachineMetrics has developed a more sophisticated platform allowing features such as high-frequency data collection and custom edge algorithms execution for analytics and machine learning models. In addition, the platform provides the possibility to link various sensors through digital or analog I/O (Input/Output) and configure them remotely [11]. Monitor-Box offers a less complicated system, which, as the name implies, is a box-like device with RFID readers, input interfaces, and operator input buttons connected to a production machine. The sensors for machine activity registration are magnetic proximity, photovoltaic, current, and movement sensors [13].

The hardware for centralized PMS solutions covered in research papers is more complex and specific to the application. On-site existing PLCs in [14] are reused to gather production data, which reduces required hardware. However, the system complexity rises, and so does the reliability, as it is realized on top of equipment specifically designed for industrial usage. The information for employee's reference is visualized on the field level through a monitoring panel. A wireless MQTT gateway is chosen for data propagation to the higher level (Cloud service).

An example of PLC integrated PMS is developed in [2], with the difference that it has been only used for PMS and not for process control. The whole system is based on industrial hardware and wired communication principles. Management level server PC is responsible for real-time data presentation, archiving, and reporting. The sensor level of the system employs industrial sensors such as conventional relays, inductive sensors, and active infrared sensors. The solution guiding manual assembly and giving process feedback in [15] is more tied to the pure information technology field from the perspective of hardware. The input layer features Microsoft Kinect 2 sensor from where the RGB image and depth information captured by the infrared camera is passed to the central computing PC. After processing, relevant data is visualized for the employee on the production floor through an industrial touchscreen monitor. The information about process flow and completion times is observable through a remotely connected client PC.

2.2.2 Communication principles

Communication interfaces and principles are critical features of production monitoring systems of any kind. The significant characteristics related to communication are reliability, connectivity, throughput, and real-time support. Industrial communications are affected by multiple factors which determine the efficiency and quality of services and applications. The physical aspects are usually easier to notice as hardware equipment and a transmission medium (e.g., electrical or optical). However, the less-obvious aspects, such as application layer protocol, highly impact the communication determining the structure of packets. The key measure for efficiency in communication protocols is the ratio of overhead and payload. The overhead describes the information needed for communication handling, added as headers over ISO OSI (Open Systems Interconnection) network model layers. Payload is useful information to be sent [18].

The most notable difference in communication principles between PMSs comes from the transmission medium. In most cases, decentralized PMSs employ wireless communication methods, whereas, in centralized systems, wired communication is more present. However, exceptions may be in hybrid communication systems involving both wired and wireless communication. The main advantage of wireless communication, especially with decentralized systems using IoT area devices, is installation time and cost. In addition, edge devices can be relocated without apparent effort.

On the other hand, wired communications in industries using robust protocols like Modbus, Profibus, CanBus, HART, and even pure analog signals as 4-20 mA, have a clear advantage in reliability [19]. Another important factor is security, especially for systems connected to WAN (Wide Area Network). An experimental analysis of the possible threats of a device representative for the field of IoT is carried out in [20]. By penetrating the system with a new version of Mirai attack, tailored explicitly for industrial scenarios, authors were able to control the actuators. In the scope of a production monitoring system, the threat of vulnerable actions towards process control is impossible unless the PMS is not directly connected to process control equipment. The main threats outside the LAN (Local Area Network) are data loss and confidentiality leaks.

In decentralized systems, the communication protocols used tend to be more in line with those used in the IoT. One of the most widely applied is MQTT, along with HTTP, CoAP, AMQP, and XMPP [21]. However, hybrid solutions containing de facto industrial protocols and IoT suitable ones in favor of interoperability are available. For example, in [22], a gateway from Modbus to MQTT is developed to extend the connectivity of industrial equipment into the IoT field. The selection of application layer protocol for such systems is highly dependent on the available mediums and requirements for data transmission reliability and efficiency. One of the differences comes from the communication method that protocol offers. For example, HTTP is used for peer-to-peer communication, and MQTT is chosen if the connection of a one-to-many device is required. Another critical aspect determining reliability and efficiency comes from the transport layer protocol used for particular application layer protocol. For example, in scenarios where data transmission has to be always guaranteed, TCP-based protocol would be preferred. On the other hand, if efficiency and, in specific scenarios, the real-time factor are more important, UDP-based protocols might be favored [21].

The communication protocol selection for centralized and industrial hardware utilizing systems is mainly based on vendor support for a specific protocol. Ethernet-based networking in the industry has created a universal basis for various industrial protocols allowing parallel usage of different protocols. For example, the system reviewed in [2] uses EtherCAT between PLC and distributed IO terminals. On the other hand, Modbus TCP/IP and ADS protocol between PLC and server PC. Interoperability and standardization issues between field and enterprise-level devices could be further solved using the OPC UA client-server-based method as in [23]. In contrast, a hybrid solution in terms of used communication principles is chosen in [14], where existing field devices (PLCs) use native industrial communication protocols. However, the connection to the cloud platform is made via wireless MQTT protocol.

2.3 Functionalities and user interaction

2.3.1 Functionalities

The PMS, like any other similar manufacturing system, is oriented to provide help in production management and processes through functionalities encapsulated into the system. The PMS could be divided down into components based on the functionality and objective of each module. An analogy to the main components of the PMS proposed in [4] is visualized in Figure 2.3. Components and functionalities dictate the achievable system performance for manufacturing enterprises, seeking an optimum point between cost, effort, and given value. The importance of customization in functionalities is high, mainly in the form of expansion to provide one integrated platform filling the manufacturing company’s needs. Each individual component could be divided into specific functionalities, from which the most comprehensive are data collection and processing parts [4].

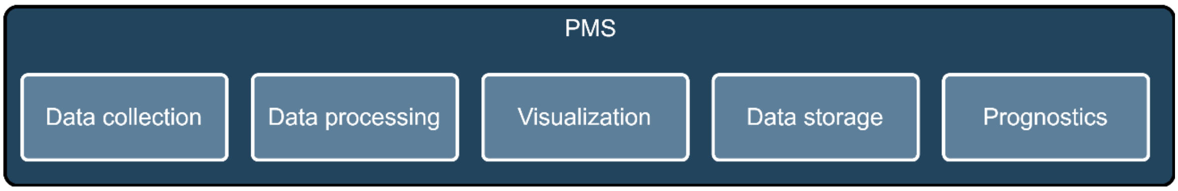


Figure 2.3. PMS components

Data collection contains the means for data acquisition from production processes, equipment, environment, and other production fields. The most significant factors related to data collection functionalities are a variety of applicable sensors and communication interfaces to guarantee integration possibility. Moreover, it is essential to define if one or another input can be received automatically or manually from the system execution prospect. Data processing acts as a medium between acquired information and the end consumer. It provides relevant information by using mathematical calculations and logical operations. The visualization component is for the end-consumer to whom the information is propagated. The key functionalities are real-time and historical data visualizing, reporting, and alarm/event displaying. The data storage module is responsible for data archiving, and the prognostics module estimates process-related parameters by applying complex calculations and machine learning [4].

The number of functionalities and their complexity varies significantly between different PMS solutions. A clear difference can be seen between solutions published in research papers and those that reached the market. Typically, the systems proposed in the research papers have a relatively narrow spectrum of monitored aspects, and they are often destined to solve a specific task. For example, systems in [6] and [8] concentrate only on a few production or environment parameters and visualize them at the management level. A broader scale of monitored values like operator information, machining time, product and order attributes, and actual machining time are collected in [5]. However, the output side remains unchanged, offering basic functions such as real-time and historical data visualization.

On the other hand, the systems sold on the market feature much more complex and sophisticated functionalities. For instance, the systems might feature job scheduling, shopfloor feedback, and automated reporting modules. Furthermore, maintenance management is a frequent addition as the PMS collected data can often characterize the need for maintenance. The theoretical concept of combining those two systems is described in [24] by proposing a PMS with integrated maintenance management functionality. Combining more functions into the PMS will raise the value given to manufacturing enterprises. However, it will also make the system more complicated and increase the service cost in the case of SaaS-type products. An overview of some additional functionalities integrated into PMS systems is given in Table 2.1. Another substantial difference comes in usage of production metrics, as solutions on the market tend to offer a more standardized approach by widely applying methods such as OEE and KPIs to enhance performance [25].

Table 2.1. Additional functionalities comparison between different PMS vendors [9-13, 26-27]

Vendor	Evocon	Global Reader	Machine Metrics	Matics	Monitor-Box
Job scheduling	x	x	x	x	x
Shopfloor feedback	x	x	x	x	x
Maintenance module	x	x	x	x	x
Predictive maintenance	-	-	x	x	-
Automated reporting	x	x	x	x	x
Direct integration with PLCs	-	-	x	x	x
Integration with ERP/MES	x	x	x	x	-
Custom edge algorithms support	-	-	x	-	-

2.3.2 User interaction

User interaction with the system is the most immediate way an employee perceives a system. The main characteristic of manufacturing activities adhering to Industry 4.0 is the integration of human factors into operations despite an advanced degree of process automation. The role of operators is continuously transitioning from a manual workforce towards decision-makers and coordinators concerning the alignment of value creation processes. Therefore, the user interaction with the system becomes more direct leveraging machine-to-human (M2H) and human-to-machine (H2M) communication. The performance of user interaction depends highly on the functionalities and assistance provided by the system and is strictly tied to the automation level of the system [28].

The presence and amount of human interaction with PMS depend on the diversity of acquirable information and the level of system automation. The importance of automation is often emphasized, aiming to provide the enterprise with expected data without requiring notable effort [5]. However, more important is to consider both phenomena together – diversity of data and requirements for user interaction. Otherwise, an autonomous system providing information in a narrow context [6] may seem preferable against more complicated ones [9 - 12] demanding manual actions. Two unique user interaction levels could be identified – field level operator and management level employee.

There appear two distinct types of user interaction in solutions proposed in research papers. One segment practices a principle of no user inputs at the field level, collecting the information only via sensors and communication interfaces [6, 8]. The other approach introduces a hybrid solution by adding operator inputs via various mediums such as RFID cards, generic buttons, or touch panels [5, 14, 15]. The observation of gathered data on a higher level requires similar user interactions with minor variations. A step above in terms of user interaction is commonly present in market solutions. Widely-spread feature of shopfloor feedback is offered by the majority of the vendors [9 - 13]. This opens possibilities to richen the data by adding comments like downtime reasons, quality notes, product information, and others via mediums provided as a part of the system (typically touch panels or computers).

The most important difference can be noticed on the management level of systems existing on the market. Advanced functionalities like job scheduling or production planning impose higher requirements on the employee by requiring more time and attention. Different purpose functionalities cover many user profiles – production manager, quality manager, and maintenance manager. As a result, the value given by the system is increased, compromising the required additional staff and workload needed.

2.4 Integration of artificial intelligence

AI (Artificial Intelligence) emerges from science fiction to become the frontier of world-changing technologies. The existence of AI in industrial applications is characterized by analytics technology, big data technology, cloud or cyber technology, domain know-how, and evidence [29]. The AI in industrial applications introduces benefits by discovering unknown patterns in data and decoding them to enhance performance and efficiency. The most prominent areas for applying machine learning are maintenance management, quality management, production planning and control, logistics, and supply chain. Learning method-wise, the widest applied is supervised learning. However, unsupervised learning and reinforcement learning are also practiced [30].

A demonstrative framework for predictive maintenance application is proposed in [31]. The platform embedding sensors is retrofitted to existing milling machines to enable predictive maintenance using supervised learning technique and neural network. A defect detection based on a supervised learning algorithm in additive manufacturing is developed in [32] to predict the porosity of the product. Input ranges prediction for productivity and profit optimization purposes is proposed in [33] by applying both methods, supervised and unsupervised learning.

Predicting the production output parameters with Machine Learning (ML) is a general topic in many fields. For example, this has been effectively used to forecast manufacturing sales of plastic injection molding machines through different indicators in [34]. Similar concepts have been applied in agriculture to predict production, harvesting area, and yield [35] or the sensitivity of factors to the production outcome [36]. A more classical production application for parameters prediction is obtained in [37], which is used to forecast the production of waterflooding reservoirs in the oil and gas industry. Finally, a short-term output forecasting concept is provided in [38]. The solution offers means to predict photovoltaic (PV) modules' energy output using environmental parameters such as weather data and historical power output data.

The presence of collected data by PMS gives a solid basis to artificial intelligence integration and is a continuously improving field. The PMS with advanced functionality in [3] is a further development of [4] proposed by the same research group. The predictive maintenance module is a new addition, driven by Artificial Neural Networks (ANN). A two-stage model was developed for tool life-span prediction. Similarly, the PMS providers on the market are smoothly widening the portfolio of features integrating ML. One of the most advanced approaches is offered by MachineMetrics [26], which has deployed ML for predictive maintenance, detecting patterns from the hundreds of data items. Apart from maintenance, MachineMetrics offers the client to build their own algorithms and deploy them at the edge devices. This gives the client the freedom to customize the algorithm based on available data and needs.

2.5 Conclusion

The existing PMS solutions have very distinct differences comparing approaches proposed in research papers, often aiming to solve a specific task, and solutions on the market, providing a wide variety of features. The primary characteristic line between systems is the conceptual structure (centralized and decentralized). The centralized systems are often custom-built, characterized by a more sophisticated system structure and a highly personalized approach to meet the company's needs. The decentralized systems are often built based on IoT, employing edge devices connected to the production equipment to provide flexibility. This is the characteristic concept of the solutions available on the market.

The most occurring hardware platforms are small single-board microcontrollers and computers or custom-developed platforms. The tendency of platforms to become cheaper and have more computational power enables the deployment of more complicated algorithms on such boards. On the other hand, reliability is the prominent weak spot of such devices. Microcontrollers are far less reliable than industrial controllers regarding the accuracy, processing capability, and life span, as they are not designed for industrial usage in the first place.

The most used communication method, especially in decentralized systems, is wireless communication, generating much freedom and reducing installation costs. Despite that, wireless communication may have difficulties in a harsher production environment due to interfering signals generated by manufacturing machines or building layout. The sensor level of the system is commonly standardized to provide integration possibilities for various devices. However, there are still areas that cannot be covered. The most challenging of them are production companies with a lower level of automation and various unstandardized equipment.

The functionalities of the existing solutions are either very basic or highly advanced. The ones described in most papers are destined for single or few parameters monitoring. A complete set of functionalities is typically embedded into the solutions on the market. The intermediate segment in functionalities is relatively absent. The typical areas for monitoring are equipment, personnel, and assets. Apart from pure production-related metrics, PMS may include modules, such as maintenance and environment monitoring. Companies providing PMS usually offer modular options where customers can choose the necessary components. The system is commonly sold as a service on a monthly basis, which may be costly depending on the number of production machines and chosen functionalities.

There are two methods used for presenting the data at the management level. Visualizing the data in raw form is mainly practiced for less sophisticated systems. In contrast, the solutions on the market are often employing more standardized and combined metrics. This gives a good overview of the production, especially in larger companies, and is often consumed by higher levels of management. For smaller companies, raw values and not combined statistics are more relevant to observing the production flow. Moreover, the calculation of such metrics may require data that might not be acquirable automatically or is totally absent.

User interaction is strongly tied with functionalities deployed by the system. Solutions on the market often use operator inputs on the production floor to accommodate specific features. This loads the employee with an additional workload. Moreover, the availability of information will rely on the employee. A similar tendency is identifiable on the management level, where more advanced systems assume more effort to manage them. The amount of effort required for user interaction strongly dictates the usability and efficiency of the system. The aspect may not be as critical for larger companies considering the amount of useful information received. However, the extra workload and staff are often not preferred for smaller companies.

AI is continuously reaching production applications and is becoming a part of data processing to monitor yet unknown patterns. AI could be implemented in different fields for prediction tasks. The immense possibilities provided could have great potential in PMS solutions. There are existing PMSs leveraging ML to realize predictive maintenance, anomaly detection in process parameters, and custom edge algorithms. Despite this, the prediction of production output is not a general topic from the perspective of PMS concepts. By combining data from meaningful inputs and factors, it may be possible to predict the company's production output.

Based on the conducted literature review, it can be concluded that available solutions are roughly divided into two major categories based on received value from the customer's perspective. One group comprises solutions providing information in a relatively narrow spectrum covering only a specific field. The other group of solutions is rich in offered options and monitoring possibilities embedding the newest technologies. However, the concerning factors are still reliability, cost, and the required amount of user interaction. Therefore, there is an apparent absence of a system for SMEs that delivers an adequate amount of data from the production site as automatically as possible while guaranteeing reliability.

2.6 Aims for the system and thesis

- Further develop the centralized type of PMS [2] for small and medium-sized enterprises including modules for:
  - production monitoring;
  - environment and facility monitoring;
  - maintenance management;
  - production prediction.
- Employ the characteristics of industrial automation hardware and software, and wired communication methods to guarantee high reliability of the system.
- Develop a system, which is maximally autonomous seeking for optimum between maximum amount of provided information and minimum required user interaction.
- Design of the PMS on a principle of one-time-investment for enterprises to optimize costs.
- Integrate new input acquiring methods from production equipment to cover broader range of enterprises.
- Create possibilities for integration of AI based algorithms.
- Develop PMS with standardized structure to be later applicable as a product on the market.
- Test the developed system practically in the footwear industry.

3. PMS CONCEPT DESIGN

3.1 Overview and requirements

The development of bigger systems, including various hardware and software components, starts by fixing the requirements, functionalities, structure, and principles. This gives the framework around which the system is to be built. The common basis and principle structure are shared with the predecessor developed in [2]. However, most of it has been totally re-engineered to offer a better user experience with a more united system. Furthermore, the newly supplemented features target to widen the monitoring area significantly and thus, enhance the gained value from the perspective of potential production companies using the system.

The developed PMS is mainly aimed for usage in SMEs to bridge the gap between costly monitoring systems and the growing need for more adequate data from production. Due to this, the peculiarities of SMEs have been specifically considered in system design. Much effort must be put into standardization and universality to pursue a system applicable in different industries. The standardization aspect is also relevant within a single system as the amount of monitored parameters and equipment grows. Ultimately, the objective is to develop a solution ready to be released to the market. Therefore, the standardization benefits to management and handling of the systems afterward.

Throughout the development process, it is essential to continuously test the completed sections of the system in real-life conditions. For this purpose, a footwear industry company was used as a testing platform for which the developed fully functional system was delivered. Continuous hand-in-hand development and testing are necessary to eliminate mistakes at the first stages and not allow populating them to further system levels. This approach is specifically crucial in software development, considering the scope of the system. Within this respect, it is crucial to deploy version control tools and methods throughout the process. The possibility of developing a system on theoretical and practical levels opens possibilities to test and validate new ideas that could lead to innovation. Furthermore, this kind of approach determines whether a theoretical assumption is feasible in reality and helps find new ways to solve the formulated issues through development. Therefore, testing is an integral part of the development and has been done at all stages of work.

The key requirements according to which the system is developed are divided into four following categories: general, technical, safety, and financial. The requirements are presented in Table A1.1-A1.4 in Appendix 1. General requirements (Table A1.1) set the abstract properties of the system, which are to be used as a basis for development. Technical requirements (Table A1.2) define the core technical features of the system and are mainly set for the hardware and software and their cooperation. Safety is one of the most important topics for any system, especially those containing electrical devices and hardware. Therefore, it is crucial to address the safety requirements (Table A1.3) throughout the process to minimize and eliminate possible human harming factors during system usage and installation. Besides mentioned, the financial requirements (Table A1.4) are also vital for the system's feasibility as a product. Therefore, it is essential to seek an optimum between system cost and received value.

3.2 Functionalities

3.2.1 Production monitoring

The broadest range of functionalities should be present in the production monitoring segment to cover the needs of companies with various types of equipment. As the objective is to give as clear and direct overview of the production as possible, the main scope is on tangible measures. They can be divided into three categories (Figure 3.1). Each function should be implemented so that it can be combined with others. Therefore, a customized functions-set for a specific type of production equipment could be assembled. This kind of architecture gives possibilities for numerous variations of monitoring functions. A single piece of equipment could have measures from all three categories. The only limitation is the physically acquirable input type and its characteristics.

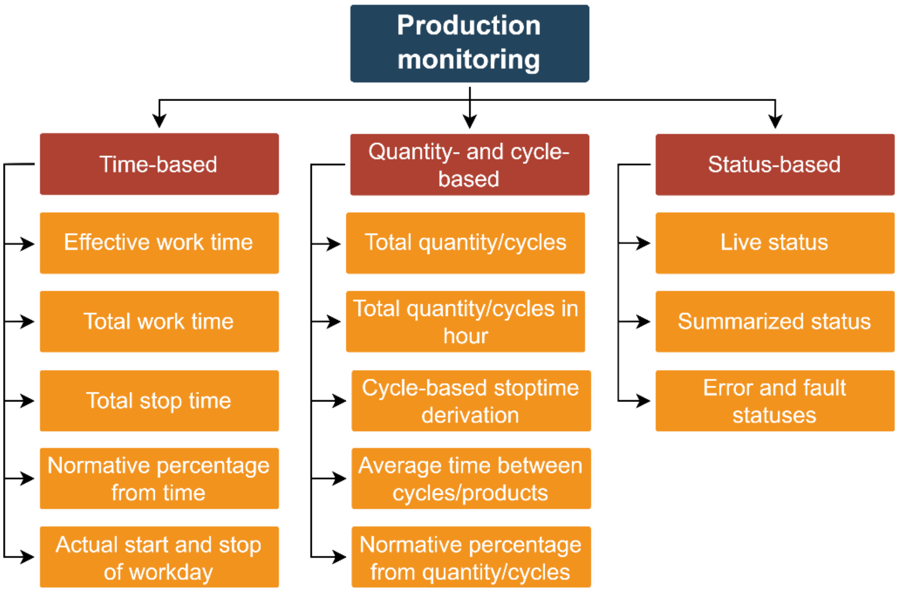


Figure 3.1. Production monitoring functions

The most primitive functions are quantity- and cycle-based ones, mostly realizable through binary inputs. However, the applicability depends on the construction of the production machine. Some of the possible options are existing end switches and relay outputs on production machines. In their absence, it is possible to retrofit them, which has a downside of increased cost and time for installation. However, the monitoring logic is easily applicable if an appropriate input characterizing the monitored parameter is acquirable.

Time-based functions are more complicated to realize. Suppose there is existing or easily integratable discrete input, and its switching characteristic over time naturally characterizes the effective work. In that case, the work time can be derived based on this. If there is no existing signal to identify equipment working status, one of the options is to equip production equipment with an additional sensor system. This approach is taken in [2], which allows monitoring the work time based on additional logic on the control level. This solution is realizable on various production machine types. However, the standardization is low as equipment differs and requires a unique hardware design.

Due to this, there is an apparent need for a universal input acquiring method for a broader range of production equipment with decreased installation time and cost. In order to develop such a solution, there has to be a physical phenomenon in common. Probably, the most common is electrical current as the production equipment is mainly electricity-based. Depending on the machine’s work profile, the current consumption value can be one of the most descriptive information sources. For example, suppose the equipment has only two identifiable states, on (consumes electricity) and off (does not consume any electricity). In that case, the work time can be directly monitored. However, the true advantage of the current consumption-based solution comes with more complicated scenarios, when, for example, the machine has standby current consumption or a specific identifiable pattern in current value. The signal can be used to collect all sorts of information, starting from work time to faults on machines indicated by high current consumption.

Besides measuring the current consumption, there are other more advanced solutions to fulfill needed functionalities. Because demands on production machines are constantly growing, more and more electronics are embedded into them. Most modern production machines feature some standardized communication bus (e.g., CAN bus) used to control the equipment. Depending on the machine, the payload may also contain diagnostic and status information regarding its current status and other parameters. Developing a medium to read the information directly from production equipment's communication bus may open new possibilities for a broader range of acquirable data. However, this approach features low standardization as each machine requires a complicated custom solution to access the information. Furthermore, directly accessing the equipment vendor communication medium may violate warranty conditions.

3.2.2 Environment and facility monitoring

Environment and facility monitoring functions are often part of PMS. Environmental conditions could greatly impact personnel and thus overall production efficiency, so it is important to monitor them. On the other hand, expenses related to the facility, such as heating and electricity, affect the company's overall operational costs. Therefore, integrating those two areas into PMS adds new visibility dimensions to the company's operations and expenses.

The environment monitoring group aims to capture the main parameters affecting indoor and outdoor conditions (Figure 3.2). The facility monitoring group features more complex parameters and possibly configuration options. By adding means to analyze the electrical parameters of the facility, it is possible to measure energy consumption and determine supply quality. The facility monitoring group contents depend highly on the facility itself and its systems. In a particular example, the possibility of integrating the heating system's web interface is considered (Figure 3.2).

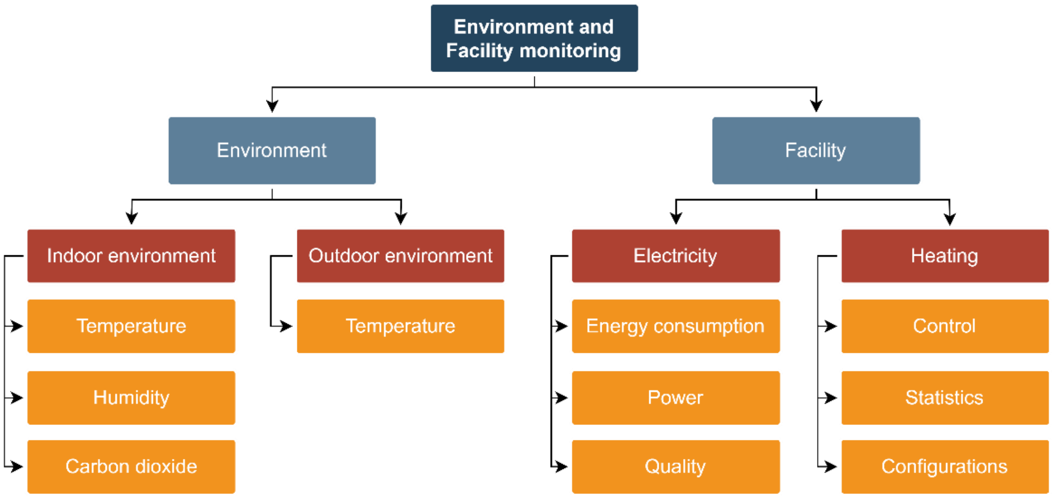


Figure 3.2. Environment and facility monitoring functions

3.2.3 Maintenance management

Maintenance management systems are helping to maintain the high availability of the production equipment and prevent downtime due to unforeseen issues. As the maintenance requirements are mostly tied with equipment usage, it is possible to utilize the information provided by production monitoring functions. Therefore, it is beneficial to consider adding features for scheduling and managing equipment maintenance to increase the overall system value.

The maintenance functions can be divided into two major categories, usage-based and condition-based (Figure 3.3). The usage-based functions form a basis for consistent maintenance, offering triggering mechanisms for time-based, quantity-based, and combined actions. The time-based function is dedicated to machines that require regular maintenance after the specified time interval. It is further divided into the component- and machine-based maintenance, which monitor a specific part or the whole machine. This creates a possibility to track the maintenance needs of multiple components on a single machine (e.g., belt, bearing, or bushing). The quantity-based function embeds the same features, but it is realized by using the number of cycles or products as a reference. The combined function offers to realize both of the previously mentioned features on a single machine if adequate inputs are available. Condition-based management acts as a supporting module next to the usage-based one. The functions are aimed to react on special occasions and anomalies. An example of this could be analog input deviating from the allowed range or digital input producing abnormal switching characteristics. [24]

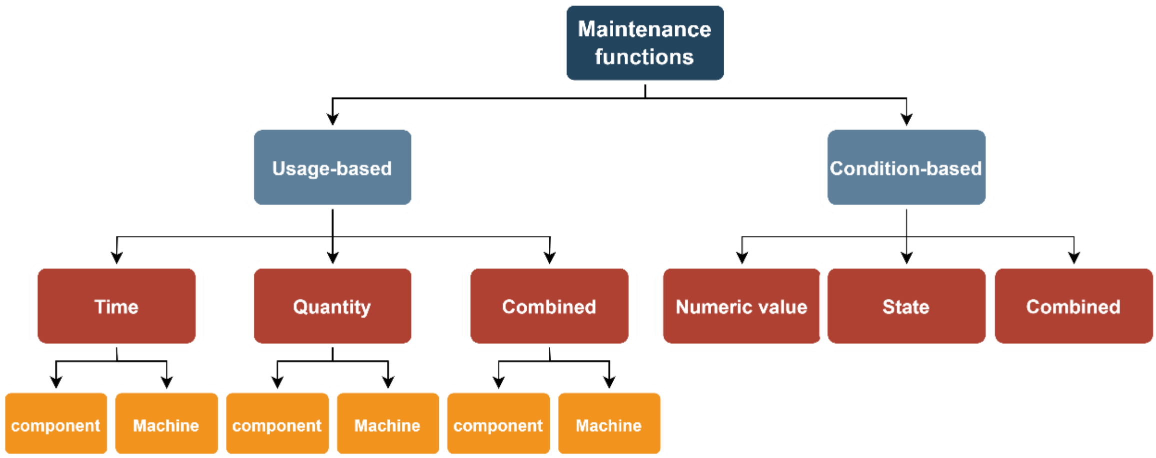


Figure 3.3. Maintenance management functions [24]

The maintenance management should be a separate logical unit from the other functions associated with specific equipment. This helps to maintain modular and standardized architecture. The function itself should be provided with means to store and manage data over a longer time, for example, a conventional database. The interface for maintenance management must be embedded in the PMS visualization to follow the principle of a united and centralized system. The visualization should include mechanisms to configure maintenance intervals and conditions and receive notifications. For example, suppose the currently running maintenance interval is getting close to the limit. In that case, the system should notify the user to conduct needed maintenance for the entire production machine or a specific component. The maintenance interval can be reset after the user confirms that required maintenance actions are performed. Similarly, if an abnormal state is detected by condition-based maintenance, the user must be notified, and the event should be logged in to the database.

3.2.4 Production prediction

Continuously advancing methods and increasing know-how have made AI accessible and applicable in various practical applications. One of the frequent applications is continuous numerical value prediction based on collected data, also known as regression. Depending on the production process, the production forecasting may not be perceptible by simple human observation and collected data. However, this may be a problem that could be solved by employing AI and, more specifically, ML methods to reveal the unknown patterns in collected monitoring data and predict the company's outcome production. The methods for such applications range from simple linear regression models to complicated Artificial Neural Networks (ANN). Besides estimated output, the models can be used for sensitivity analysis in order to distinguish the parameters affecting the production outcome the most.

The company used as a test platform features highly varying production flow and a sufficiently long production process (7-10 days). The fact that productivity is highly dependent on the human factor makes it both difficult to predict and a good concept validation platform. Before leveraging ML models for production outcome estimation, the relationship between the searched output and other collected parameters must be analyzed and distinguished to verify the feasibility of further developments. For this purpose, a preliminary correlation analysis was conducted on the data recorded at the same company with previous PMS before this work. The analysis covered 13 parameters (worked time, performed cycles, produced products) recorded with a sample time of one day for approximately one year (207 records without weekends).

The analysis indicated considerable dependencies between produced products and five other collected parameters with a correlation coefficient ranging from 0,20 to 0,35. It was particularly interesting that the relations were also found for equipment whose work tasks are relatively early in the production process and the use is occasional. Furthermore, to widen the segment of the possible inputs, the outdoor temperature of the facility location was included in the analysis for testing purposes. Unexpectedly, the temperature had a considerable negative correlation (~0,25) with the amount of produced products.

Despite an identified correlation between some of the parameters, the available set was still small in the number of parameters and records to start developing reliable prediction mechanisms. This was also one of the reasons for applying the PMS on a larger scale and including new monitoring areas at the test platform. Therefore, the newly built system features additional value by being a future test system on which to develop and investigate ML integration options. In order to cover the prerequisites for applying prediction methods, which are meaningful inputs and an adequate amount of data, three different fields are considered within the new system (Figure 3.4).

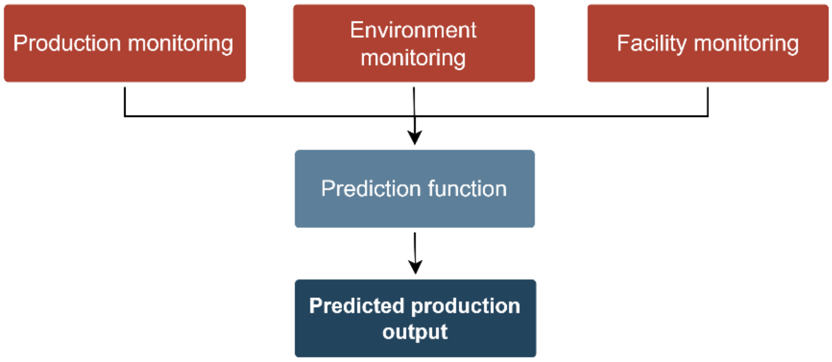


Figure 3.4. Production prediction function principle structure

The technical side of the prediction algorithm could be divided into two logical parts. One contains the model used for predicting the values, which must be determined based on the particular production company's prediction needs and acquirable data set. The other important part is the data collection and handling. Resource-wise, the algorithm utilizes similar features as maintenance management. It requires access to historical data in the database and current data from the monitoring modules. The production output prediction should be made at the end of the workday for the next day(s). In order to provide meaningful inputs from different monitoring areas, additional data processing should be considered. For example, parameters such as average temperature and total electrical energy consumption during the workday.

3.3 System structural concept

3.3.1 Logical levels of the system

The new version of PMS utilizes the same centralized structure with three levels as its predecessor, shown in Figure 2.2 (chapter 2.1.3). The system's field level (Figure 3.5) does not have fundamental changes apart from new input acquiring methods and sensor systems. The only new addition is external extensions which include all sorts of plugins possible to integrate into the system (e.g., heating management web interface). Although those plugins could handle more complex management than physical inputs, they are still considered field-level entities as they are not original to the system. Logically, they are part of the input acquiring layer and routed directly to the visualization server.

The majority of the changes affect control and management levels to make the system more united. This could be achieved by concentrating system control and services to control level as much as possible. Leveraging such an approach reduces constraints between two levels and makes the control level more independent. As a result, integrating PMS into the company's existing systems is easier, and management-level hardware requirements are less strict. The only disadvantage is the higher performance required from control-level hardware.

The most significant change in system structure is related to visualization. The new version implements a visualization server on control and clients on the management level (Figure 3.5). The fully functional access to PMS from any compatible client is made directly via a control-level visualization server. This grants more convenient and flexible access to PMS data and controls. The only components tied to a specific server device are the database and reporting engine. The variety of options for databases and commonly higher availability of memory allow using relatively any standard PC as a database server. Reporting engine requires specific software to run the services, and therefore it is not applicable on the control level. However, in the system context, the presence of reporting engine is optional as it is a separate software entity.

Thanks to the new design, the control level (Figure 3.5) packs most of the system functions. The data exchange and control with the management level is realized through a database driver, different communication drivers, and a visualization server. The core monitoring algorithms are gaining inputs from the physical field level. The output parameters (e.g., work time, produced quantity) are populated to the visualization server, communication drivers, maintenance management, and prediction module if needed. The maintenance module uses monitoring data and a database driver to exchange current and historical data with the database to drive maintenance-related actions. Prediction algorithms use similar resources from the system except for input parameters as they differ. The supportive system functions are general features required to execute the system, whether hardware-specific or needed for a certainly developed algorithm.

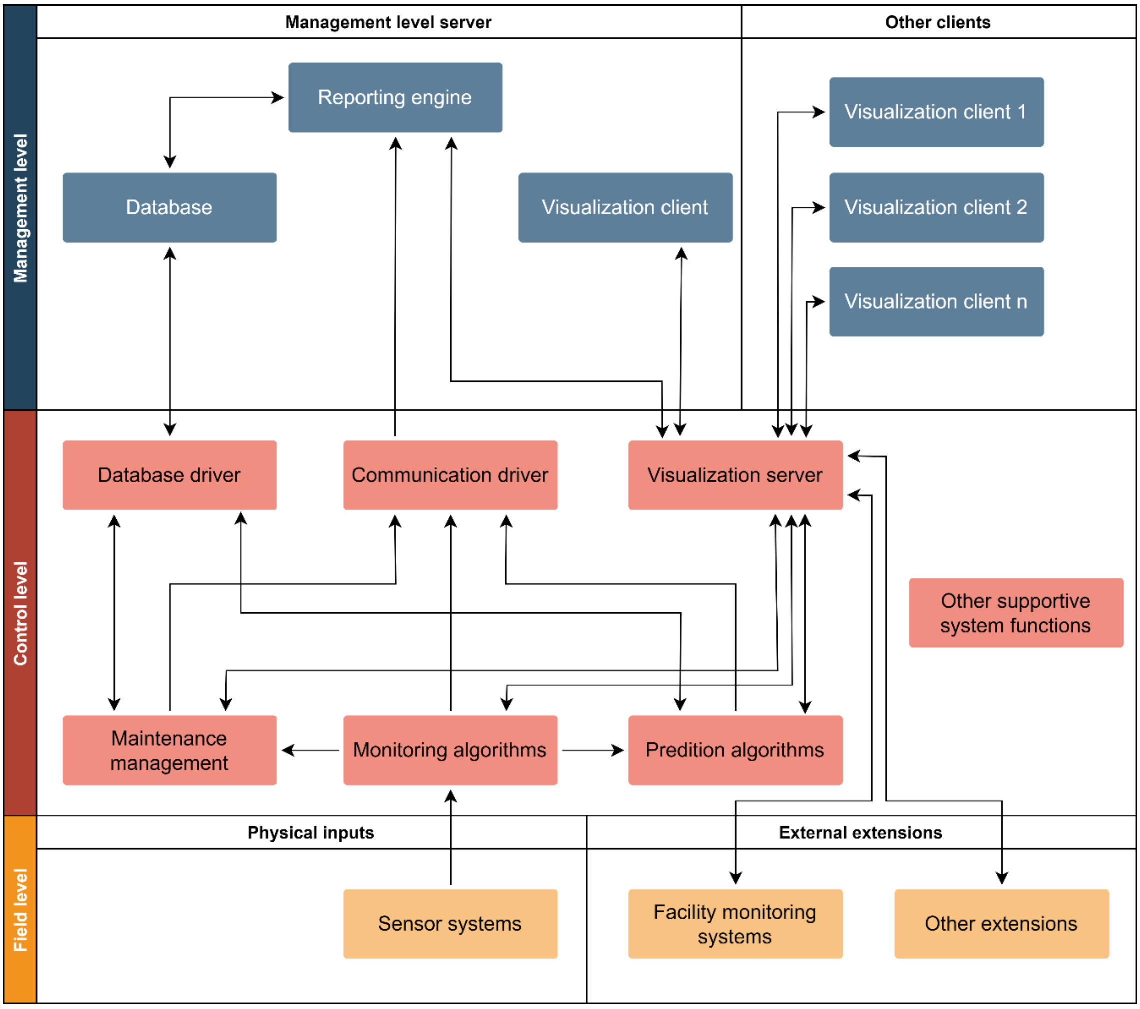


Figure 3.5. System structural concept by levels

3.3.2 Algorithm structure

The core of the PMS is mainly formed by monitoring algorithms, and the way inputs are processed to derive parameters of interest. The construction of those algorithms strongly determines the generated value and the system's reliability. From the system architecture perspective, they can be divided into two groups. One group contains functions providing necessary services and data for all monitoring algorithms. An example of this could be an instance that provides information such as elapsed time of workday, flags indicating if the monitoring should be active, triggers for calculations, saving and resetting the data, and many more. The idea is to compile administrational data creation and handling into logical groups where they are available for all the monitoring algorithms. This avoids unnecessary resource usage where the same data is created in multiple places.

The other group contains algorithms for monitoring specific production equipment. Those are assembled from standardized functions covered in Figure 3.1. In order to achieve the modular structure of the system, each production machine should have a single dedicated monitoring algorithm. This helps build the control platform piece by piece without overcomplicating the system. Furthermore, such an approach allows modifying and adding monitored devices. A general example of a single monitoring algorithm with inputs and output is given in Figure 3.6. Inputs to the monitoring algorithm are physical input signal, set of administrative data, and set of user configurations. The output is equipment monitoring data which can be directly presented to the user.

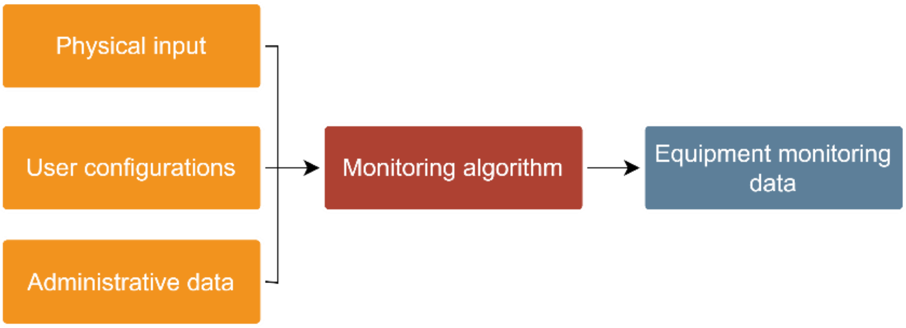


Figure 3.6. General structure of single monitoring algorithm

Another critical factor to consider during development is variables structure and methods for handling them. As with more extensive systems containing hundreds of input, output, and internal variables, their structure plays a crucial role in whole system observability. Therefore, it is important to compile variables of similar purpose or properties into structural sets that can be linked with a specific algorithm. An example associated with Figure 3.6 is a data structure containing user-configurable parameters (User configurations). This set may include equipment identifier, monitoring algorithm settings, and others.

This method makes it possible to create standardized structures for each specific algorithm. They can be later reused for similar algorithms with confidence, knowing that all the required parameters are present. Furthermore, it is possible to create separate lists of structures containing similar purpose datasets to refine the variables' architecture further. For example, all the configuration data structures for monitoring algorithms are part of a single list. This helps standardize the whole system and will result in significant benefits if debugging is needed. Moreover, leveraging this concept helps integrate variables to further system levels, for example, into visualization.

3.4 Operating principles

3.4.1 User interaction and user interface

The system must be as autonomous as possible, following the design requirements. This helps to guarantee minimal user interactions and easy management. For achieving this, an optimum has to be found between the extent of the provided information and user inputs such as product quality information. In the scope of this development, there has been a decision not to include any manual information-gathering devices at the field level. Instead, only sensor systems are used to produce inputs regardless of operator actions. This helps avoid loading the operator with additional duties and guarantees stable data availability.

A similar approach is taken on the management level of the system, where the user can obtain information and is not obliged to enter any additional data such as job scheduling. Therefore, the system is targeted to provide as much data as possible with intelligent algorithms without any user inputs. In this configuration, the PMS is a supportive system for production companies with low management requirements, which is especially important for SMEs. It provides the management with the most urgent production data, such as produced products, work cycles, work minutes, and statuses.

The visualization of collected data has to follow the principle of neutrality. Monitored equipment units should be displayed uniformly to have a user interface pleasing to the human eye. Using abstract shapes such as rectangle makes it possible to avoid variegated and confusing views. The disadvantage of this approach is possible confusion between equipment. This can be solved by positioning the symbols similarly as they are located on the production floor. Additionally, each symbol should be equipped with a unique identifier of the equipment. The symbols should contain only the most relevant information in the main user interface view to avoid overloading the picture. Detailed information and configurations can be accessed by opening the popup from the symbol.

In order to make the visualization easily observable, the monitored equipment symbols should be equipped with color identification. The color palette should have a few colors to identify equipment levels of efficiency. This allows the creation of color scheme logic where less efficient machines are displayed with more glaring colors to draw user attention. However, the neutrality of the view should be maintained as much as possible, which can be performed using pastel colors. Similarly, the fault and other statuses should be visualized. The colored status identification should be applied only to the essential equipment symbols. This helps to distinguish between primary and background information. An example of a background information source could be environment parameters, as they are not the most critical from the perspective of production efficiency.

Another critical factor for achieving easily manageable and flexible PMS is configuration possibilities, especially the ones doable during system usage. The main parameters affecting system behavior must be accessible through the user interface. Therefore, it should provide means to adjust system execution parameters, for example, manually starting and stopping the monitoring if needed, configuring the workdays schedule based on date and time, and adjusting the percentage of efficiency levels. Similarly, the monitoring algorithm settings should be configurable individually and group-wise for all similar monitored entities to allow faster system tuning at first startup. Furthermore, there should be primitive configuration and personalization options, such as themes and localization for the user interface itself.

3.4.2 Input signal processing methods

The functions within the monitoring algorithms are executed by applying certain mathematical and logical operations to physical inputs. The most straightforward yet limited segment for applying those methods in production monitoring is discrete inputs. The parameters of interest can be produced using several counters, triggers, and timers operated based on created logic. Additionally, they can be equipped with various average calculations, for example, the average time between work cycles. The work time monitoring is solvable using flags that are operated based on user-configured timeout. If a specific timeout is exceeded after the last input, the passed timeout and currently running time are considered as stop time. The acquirable amount of information can be further enhanced by using several inputs from a single machine. For example, depending on the machine type and construction, it may be possible to use inputs that characterize work cycles and work time.

Analog inputs offer more possibilities as they carry a wide range of continuous values in time. An example of an applicable analog signal given in chapter 3.2.1 is the current consumption of the production machine. Depending on the current consumption profile, there are many options for capturing required parameters (e.g., work time, work cycles, statuses, and faults). In the simplest solution, if a machine has current consumption and effective work characteristics overlaying, it is straightforward to monitor work time. If there is no or minimal current consumption, it can be monitored as stop time. On the other hand, the work time monitoring timer should be started if current consumption exceeds the configured threshold.

This method is not the most versatile, especially for equipment that has standby current consumption if it is turned on, but no work is performed. An example of such a current consumption profile is given in Figure 3.7. Theoretically, it can be solved by configuring the threshold value (blue line) to the exact level where the machine goes from standby to working mode (orange line). However, this method has disadvantages as it requires current consumption measuring and analysis for each machine to determine the precise threshold value. Moreover, if the threshold changes in time due to changes in the machine's behavior or added accessories, the monitoring cannot be trusted and has to be reconfigured.

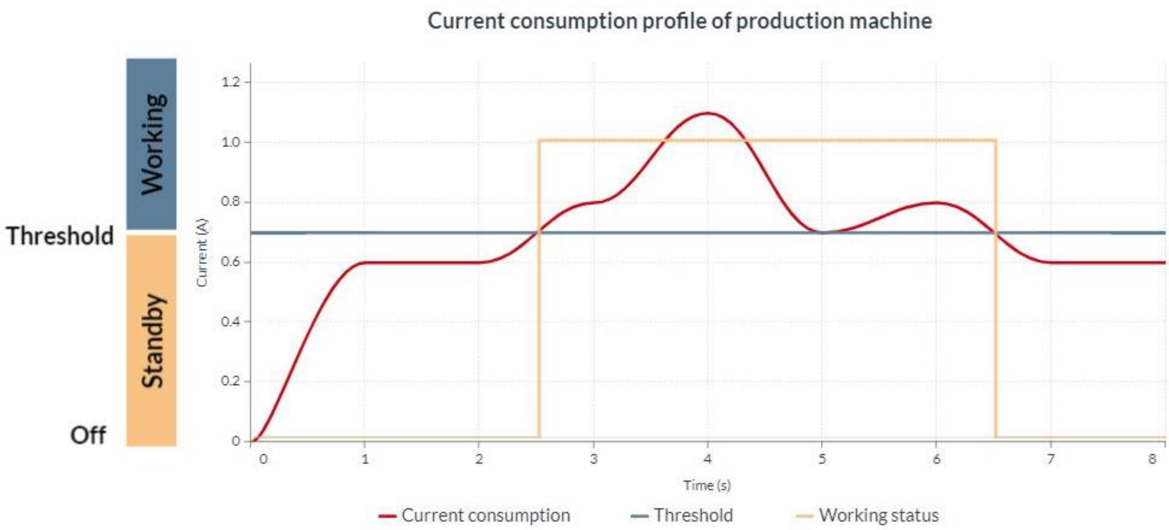


Figure 3.7. An example of the current consumption profile for the machine consuming electricity in the standby state

In order to make the system more intelligent and avoid recurring timely configurations of the threshold value, there are two options. One is to integrate the automatic threshold value calibration into the system. The calibration should be conducted when the production machine is in standby mode. The calibration algorithm measures the current consumption during a specified time and finds the average to which a margin is added. The calibrated value is the threshold above which the machine is considered to perform practical work. This calibration algorithm can be triggered by the user or the system itself from time to time to guarantee accurate monitoring. However, precautions should be taken in creating this algorithm to determine whether the machine is in stable standby mode and the calculated threshold is realistic.

Another option is to reduce the need for accuracy demanding calibrations. This can be resolved by monitoring the work status based on the current change in time by applying standard deviation calculation. The algorithm should calculate the standard deviation for configurable length in time, for example, the previous three seconds. The decision should be taken based on a similar standard deviation threshold value. However, the accuracy requirements for the value are less strict, and it is not sensitive to the change of base-level current consumption. This kind of approach is limited to only varying current profile machines or those that perform work with constant but short current pulses to be detectable via standard deviation.

Another group of analog signals is the ones that require filtering over time to provide stable readings and disturbance rejection. Those are, for example, environmental parameters such as temperature. Due to the natural behavior of the parameter, it cannot change quickly over time, but the reading could be sensitive to disturbances near the sensor. Therefore, additional filtering should be applied with a running average over a specified time. Furthermore, to detect errors in signal, it is possible to employ additional logic. As environment sensors generally feature a wider measurement range than required, it is possible to determine primitive errors from the input signal. The monitoring should be equipped with lower and upper boundary values, under and over which the reading is considered faulty. This may indicate electrical or mechanical failure with the sensor, lost connection, or faulty input receiver.

4. HARDWARE AND SOFTWARE COMPONENTS

4.1 Hardware selection

4.1.1 Control level hardware

The selection of hardware components is based on a system installed in a footwear industry company. The selection is made in the order of prioritization of more important components. Considering the fundamental idea of the concept to build a PLC-based PMS with centralized architecture, the essential part of the hardware is PLC itself. Another criterion that prioritizes the PLC selection is that this is the central control hardware to which all the control level functions are concentrated. It has the most ties with other system components. Thus, it must be selected by acknowledging the integration possibilities and offered functionalities. The decision of central control hardware determines many of the system sub-components.

The term PLC might be misleading in the context of this system. Conventional generic PLCs, intended to provide simple control logic, could handle numerous physical devices and offer means for basic control functionalities. However, due to the nature of a PMS, most system intelligence and value are gained through signal and data processing in the PLC CPU, which stresses its resource and capabilities requirements. Therefore, it is essential to understand the level of performance awaited from the PLC from the perspective of memory, computational power, and connectivity options. Such more advanced devices are outgrown from regular PLCs, often called industrial PCs or embedded PCs. They pack a broad range of features to fulfill all sorts of control tasks.

Even though the PLC was chosen during the development of the first version of PMS in [2], the procedure was repeated to either confirm or deny the selection. Mainly due to increased system requirements and advances in this technology field. Furthermore, the selection and evaluation were made more systematically, considering the platforms as a part of the standardized solution. Besides technical parameters, the innovativeness of the candidate platform was evaluated, as it plays a significant role in future developments, especially in the context of PMS. The likeliness of a vendor to integrate new trending features highly determines the viability of a product in which the PLC is a central control device. All major automation hardware companies like Siemens, Allen Bradley, ABB, Beckhoff, Mitsubishi Electric, Schneider Electric, and B&R were considered.

After conducting the first evaluation of possible platforms, two vendors were filtered out, Siemens and Beckhoff. However, further analysis revealed that Beckhoff is still a more flexible option for a PMS solution. First, Beckhoff features a better cost to performance ratio and a free engineering environment, which is vital for the system's overall cost. Siemens is relatively fixed to its product family compared to Beckhoff regarding integration possibilities. As Beckhoff runs on Windows operating systems, it allows embedding custom applications into it. Furthermore, the innovative approach to embedded functions advancing toward traditional PC programming instead of an isolated automation sector enhances easier integration. This leaves freedom to widen the functionalities portfolio in the future.

The PLC model must be chosen explicitly considering the proposed features in the PMS concept design. The main outstanding criteria functionality-wise are the capability to run visualization server and ML algorithms. The memory and computational power should be estimated by considering the amount of monitored equipment (tens to a few hundred). The optimal PLC filling those requirements is Beckhoff CX5140 (Figure 4.1), featuring a 4-core processor and a sufficient amount of memory (4 GB RAM). Another critical option is the operating system version, which must be Windows 10 to run all the needed services. Technical parameters of the PLC are presented in Table A2.1 in Appendix 2.

Figure 4.1. PLC CPU module Beckhoff CX5140 [39]

Thanks to the PLC’s general purpose of being control hardware explicitly designed for industrial usage in a harsh environment, it complies with strict EMC and mechanical vibration standards. However, due to the IP20 protection class, it should be installed into a dedicated cabinet to protect it against smaller objects’ impacts (e.g., production waste particles) and liquids. This also helps guarantee personnel safety by separating the device from the production environment.

In order to simplify the installation and decrease the cost of cabling, the I/O couplers and junctions should be considered. They are used for distributing the I/O terminals according to the needs coming from the production building layout and location of the monitored equipment. Based on the layout of the test platform company, the I/O junction (EK1122) is used in the main cabinet next to the PLC. This allows to distribute the I/O terminals into two other cabinets where they are connected through I/O couplers (EK1100). The PLC I/O terminals connected to the communication bus are inseparable from the PLC CPU module and I/O couplers on the control level. Despite this, they are chosen together with field-level sensor systems as they are strictly dependent on the medium present at the sensor.

4.1.2 Field level hardware

The field-level hardware selection focuses mainly on the newly added sensor systems in PMS. As the base structure is utilized from the previous PMS version [2], the selection of components such as power supplies, cabinets, and installation materials is not in the scope of this work. The technical details of the hardware, except the base structure, are presented in Appendix 2. Table A2.2-A2.3 reflect technical data regarding the sensor systems and I/O terminals.

One of the crucial aspects of PLC vendor selection was the portfolio of available field devices. In order to realize the equipment monitoring based on electrical current, the chosen vendor offers an innovative ecosystem for measuring and analyzing electrical data. The concept features current transformers and power measurement I/O terminals. The current transformer scales the electrical current to the acquirable range for the I/O terminal (0-1 A). Therefore, the current transformer is a so-called dummy, responsible for only scaling the signal. All the analytics is performed in a terminal equipped with multiple channels. This allows to install the sensitive measuring devices into separated PMS cabinets, away from potential impacts near production equipment.

There are two types of current transformers with various measurement ranges (1 A up to 5000 A) and accuracy classes. The particular type of transformer, ring- or coil-type, needs to be determined based on installation possibilities (around the cable or connected to the terminals). The measurement range is selected based on the maximum current consumption of the equipment plus buffer to make sure the I/O terminals input current is not exceeded. Furthermore, the architecture of the electricity network and protection devices in the network and at the machine should be considered to protect the measuring circuit. The required accuracy depends on the smallest amount of change that has to be identified. The transformer consists of primary and secondary sides, where there are more windings on the secondary side (Figure 4.2). This allows linear scaling of the primary side current according to the windings ratio.

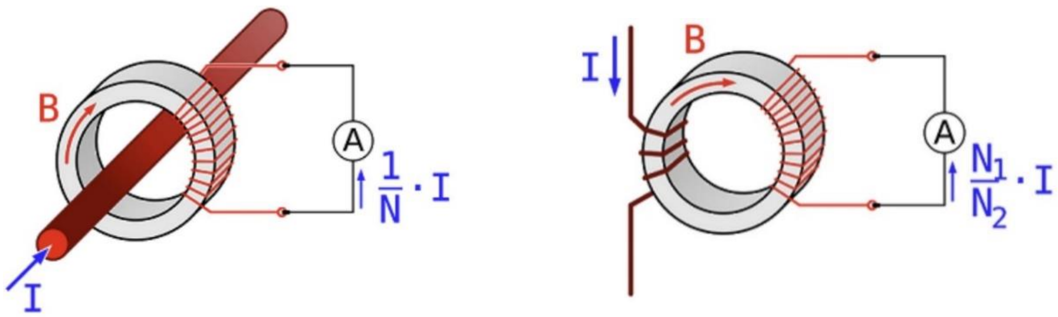


Figure 4.2. Working principle of ring-type (left) and coil-type (right) current transformer [40]

The power measurement I/O terminals can handle either purely current measurements or current and voltage combined. The current only terminal can measure up to six channels, providing basic current parameters and indication flags. Those terminals can be used for production equipment monitoring. The current and voltage combined terminal unlock many more observable parameters, for example, electrical power, energy, power factor, and others. Furthermore, installing a single unit of this into the same network makes it possible to measure the electrical power and energy via current-only terminals as the voltage data is populated across the system. The combined terminal fitted with a three-phase current transformer is suitable for measuring and analyzing the electrical parameters of the whole facility. An application example of three-phase power measurement is shown in Figure 4.3.

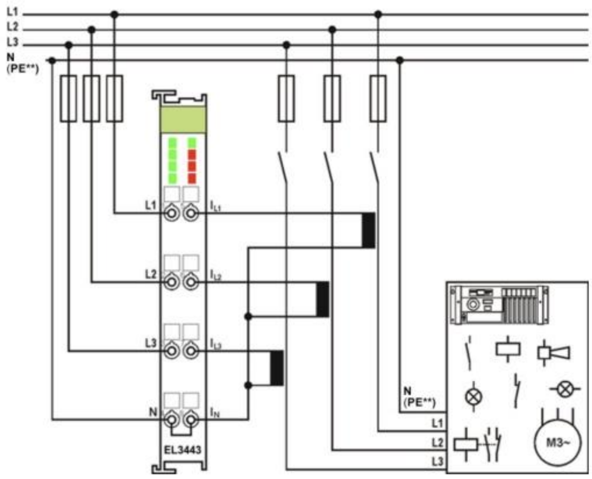


Figure 4.3. Example of power measurement at a three-phase machine [46]

The biggest group of monitored production equipment (sewing machines), in particular PMS, have similar maximum current rating (~2 A) and profile. Thus, those can be monitored using the coil-type transformer (SCT0121-0005) with a measurement range up to 5 A (Figure 4.4). The current signals from transformers are collected into six channel current measurement terminal (EL3446). The whole facility's electricity monitoring is solved with a three-phase ring-type transformer (SCT3111-0050) with a measurement range up to 50 A per phase (Figure 4.4). The current and voltage data are read via the combined power measurement terminal (EL3443). The technical parameters of selected current transformers and measurement terminals are presented in tables A2.2 and A2.3 in Appendix 2.

Figure 4.4. Coil-type transformer SCT0121-0005 (left) and ring-type SCT3111-0050 (right) [40]

Another significant group in the production monitoring hardware field is all sorts of digital inputs. Ideally, the existing signals from equipment are used (e.g., end switch, relay output). In this case, only the digital input terminal is needed on behalf of PMS. However, an additional sensor system should be integrated for machines with no existing signal to be reused for monitoring. For this purpose, different approaches were developed in [2]. Some of the developed methods, which have been tested over a longer period and have proved to be effective, will remain in the new version. For example, the working status of the sewing machines can be obtained through installed inductive sensors detecting metal objects moving either linearly or radially. For product counting, an active infrared sensor can be deployed. The technical parameters of additionally required sensor systems for realizing those methods are presented in Table A2.2 in Appendix 2.

The next topic in field-level hardware is environment sensors. For indoor measurements, a multifunctional sensor with three outputs is considered (temperature, humidity, carbon dioxide). Using a single sensor to measure all the parameters makes it possible to reduce the installation time and cost. However, attention should be paid to the sensor's accuracy and calibration, as they are more complicated devices with possibly higher potential to produce inaccurate measurements. Therefore, only sensors with vendor calibration certificates were considered. After evaluating possible options, a sensor from vendor Vaisala was chosen (Figure 4.5). The sensor is equipped with three voltage outputs (0-10 V DC) powered by a 24 V DC supply. As the sensor includes sensitive electronics, it should be additionally protected with an external fuse at the PMS cabinet. A detailed description of technical parameters and measurement ranges is covered in Table A2.2 in Appendix 2.

Figure 4.5. Vaisala GMW83RP environment sensor (temperature, humidity, carbon dioxide) [43]

In order to capture outdoor temperature, a traditional RTD (Resistance Temperature Detector) sensor PT100 and temperature transmitter (E2163) were selected from Evikon (Table A2.2 in Appendix 2). The PT100 with a 3-wire configuration is connected to the programmable temperature transmitter, producing 4-20 mA output based on configured scaling and settings.

The I/O terminals selection is made by accounting for the specific information given in sensor systems' datasheets or the behavior of the acquirable signal. The discrete signals are collected via digital input terminals. The applicable ones are the most generic 24 V ones, differing only in the number of channels and connection technology (e.g., 1-wire, 2-wire). If a very fast-changing input is to be read, the input filtering time should be considered. This, for example, applies to detecting a protruding metal object on a fast-rotating sewing machine shaft using an inductive sensor. The analog input terminals have various options due to different signal types and ranges. Conventional 4-20 mA and 0-10 V analog inputs are used in a particular project. For a technical description of all the I/O terminals, see Table A2.3 in Appendix 2. This list also reflects the hardware selected for the previous version of PMS [2] that will be applied in the new one.

4.1.3 Management level hardware

The management level of the PMS is designed intentionally with as few mandatory devices as possible. The concept includes multiple clients accessing the PMS collected information, but whose presence is optional and may vary in time. Therefore, the only hardware resource required is a single server computer running on Windows 10 operating system. However, a physical server PC is still optional as it is required for only two functions, to store a database and run reporting services. An example of management level architecture and its connection with the control level, based on the system deployed at the test platform company, is given in Figure 4.6.

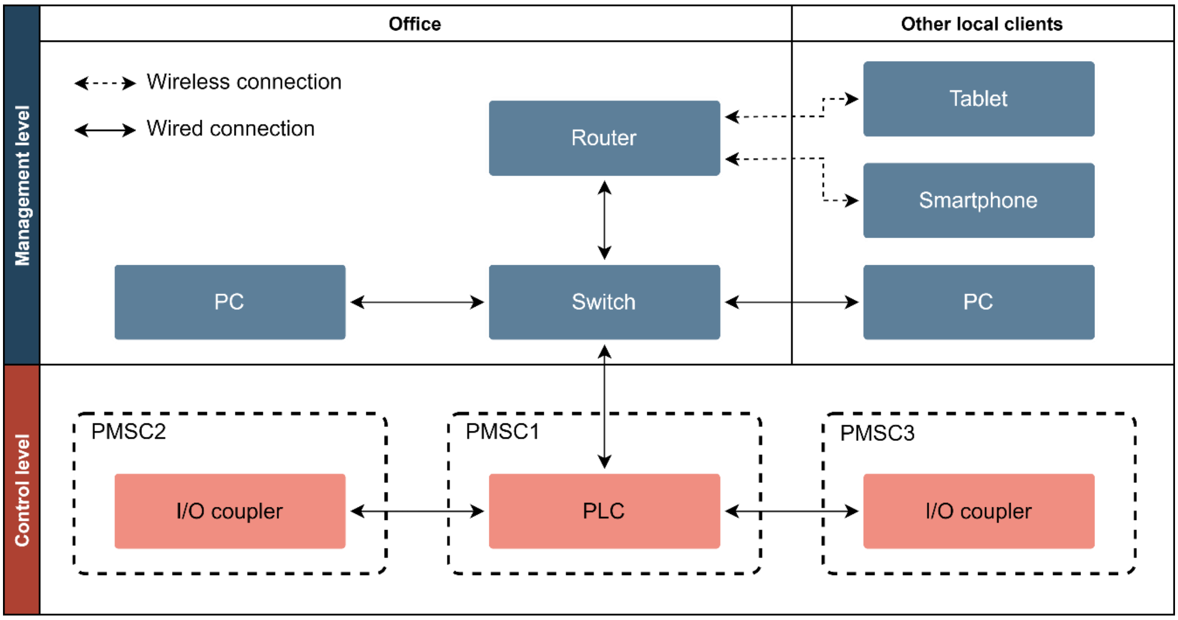


Figure 4.6. Main hardware architecture (PMSCx – Production Monitoring System Cabinet x)

Since the reporting function is optional, the system may be assembled without it. In this case, the lighter version of the database could be hosted in control-level PLC. Another option is to use some remote PC or free cloud-based storage to store the database. Similarly, there is a theoretical possibility of procuring a cloud-based virtual machine service to run the reporting software. However, this does not align with the financial requirement of the system to be a one-time investment, as such services are usually periodically billed. Furthermore, the web-based solution may introduce additional risks depending on the required confidentiality level. Another alternative is to reuse some existing PC at the company, typically assigned for other tasks, if adequate free resources are present. The only criterion is that they have to be available if monitoring is active, mainly during the workday.

4.2 Software selection

The most significant change in the used software components is in visualization software. The previous version of PMS was running on SCADA (Supervisory Control and Data Acquisition) software, which places strict requirements on the management level PC. Furthermore, the traditional SCADA software is usually heavier, as they are meant for more complicated process control. There are options for lighter versions of SCADA together with web access. However, the data acquisition server is still mainly realized on a dedicated PC. Therefore, there was an apparent need for more flexible access to the PMS.

The PMS concept design states that centralizing the visualization server into the control level would be a solution. This helps solve many integration issues between PLC and external visualization software and generally speaks for a more united system. This option was considered during PLC selection, and the chosen vendor Beckhoff provides a new type of visualization software named TwinCAT HMI [48] designed for small to medium-sized applications. Supplemented with the newest web technologies such as HTML5 and JavaScript helps gain platform independence. The responsive and auto-scaling application can be opened by any client having a compatible web browser (e.g., PC, tablet, smartphone).

The visualization server, which can be run on a PLC, makes the PLC program and visualization development much more direct as the software is designed to work together. Everything takes place within the same device, and no external communications are present to exchange data between the PLC program and visualization. The software requires at least one server license for permanent usage, including a single client. If more clients are needed, additional licenses can be added. All licenses are charged once, and the license management is embedded into the PLC project.

Another substantial component is reporting software, as it is often a key component of any data collecting system. Providing means to generate reports automatically or based on needs contributes highly to the perceived value as the user can obtain the essential statistics quickly and seamlessly. However, there is a downside as the more advanced software is usually costly. Due to this, reporting function should be integrated as an optional part of the system. It should be intentionally set up as a separate unit with data logging from control level PLC. The reporting software is transferred from the first PMS version, as it has proven to be a reliable and value-adding addition to the system throughout the extended testing period. The software is provided by Ocean Data Systems and is named Dream Report [49].

Even though the application was already implemented before, not all the functionalities were utilized there. The software package could be divided into two parts from the client's perspective. One is the reporting engine installed on the PC, which is responsible for driving the whole system. It handles all the data collection, storage, and report generation. In addition, it includes an interface that can be used for manual report generation. The second part which was not implemented is a web interface. It provides the user with the same set of tools but allows access over the web through a conventional browser. Furthermore, it integrates possibilities to create interactive web reports and dashboards to bring more flexibility into reporting.

The most complicated part of the software is the control level PLC program. It includes multiple components to realize all the tasks required for system control. As the PLC engineering environment is free of charge, the vendor implements costing based on implemented functions. The generic functions allowing to fulfill most of the tasks are covered in the PLC CPU license required for permanent runtime usage. More advanced or specific functions offered by the vendor can be imported from libraries requiring an additional license. As the objective is to minimize the system cost but enhance the reliability and value, it is crucial to consider the necessity of each additional function requiring a separate license. Therefore, separately billed functions should be replaced by self-composed ones if feasible and the outcome is reliable. Otherwise, the corresponding license is issued from the vendor. The whole list of required licenses is present in Table 4.1.

Table 4.1. List of required PLC licenses [50]

License	Description
TC1200	PLC CPU
TF2000	HMI Server (including 1 server and 1 client)
TF3800/TF3810	Machine learning/Neural network inference engine
TF6250	Modbus TCP
TF6420	Database server
TF8010	Building automation basic

In order to cover the principle execution of the monitoring system, four licenses are needed, TC1200, TF2000, TF6420, and TF8010. The TC1200 is a PLC CPU license incorporating the most needed functionalities. The TF2000 covers a visualization server and also one client. The TF6420 is needed for communicating with an external database, for which MS SQL Express is used. Finally, the TF8010 offers multiple triggering mechanisms based on time. The other two licenses are required for prediction and reporting functionality. TF3800 or TF3810 (depending on the implemented model) are for machine learning algorithms execution, and TF6250 is for communication with reporting software.

4.3 Practical implementation and setup

4.3.1 Prerequisites

One of the critical parts that shape the price of the final solution is the time required for installation. The centralized type of PMS makes a tradeoff between installation time and reliability by using industrial-grade hardware and communication principles that impose more time for installation. However, the installation time is highly dependent on the monitored equipment and infrastructure in the production company. Production monitoring is most vulnerable in terms of installation time, as environment and facility monitoring commonly face more standardized systems. If the PMS sensor systems integration into production machines requires a custom approach, such as monitoring via additional sensor systems as an inductive sensor, the installation time increases. However, if the newly developed current consumption-based solution is applicable, the installation time could be reduced significantly as the installation affects only the electrical supply line of the machine. However, this method still introduces some prerequisites to guarantee human and equipment safety.

The current transformer must be installed on the supply line, followed by only one monitored machine. This generally means closer installation to the machine as usually a single mainline is distributed down to separate machines. This, in turn, means that the safety aspects near the operator should be considered. Furthermore, as the current transformer is connected to the electricity distribution network, the network should be equipped with proper protection devices to guarantee the safe operation of the system. Finally, the cable and its installation must conform to the requirements set with electrical installation standards.

The electrical system present in the test platform company did not comply entirely with those requirements prior to PMS installation. The sewing machines opted for monitoring were powered from old sockets installed on walls, and there was no suitable location for the current transformer installation. In addition, a major part of the existing electrical supply network featured old aluminum cables, and the circuitry did not feature sufficient protection devices. Considering those shortcomings, the decision was made to go one step further with the PMS installation by rebuilding the entire supply cabling for monitored devices. This kind of approach for PMS installation is an exception as it usually would not affect the cabling other than the specific installation location of the current transformer. However, accounting for the safety aspects and pilot run of the system, it was crucial to minimize all possible risks.

The rebuild affected the whole floor’s electricity system, including 28 production machines (sewing machines), lighting, and other equipment such as air conditioning units, ventilation- and security system. As a result, the whole electricity system in this production section was rebuilt. In total, around 160 hours were allocated for rebuilding the electrical cabinet and the whole cabling. This also included the installation of cable trays for the proper installation of PMS signal cables. The outcome of the rebuild was new and adequately protected electrical circuitry forming a solid basis for the PMS integration and testing. The technical details of the rebuild are not covered in this thesis as it is not the core idea of the work and was performed due to shortcomings in the existing environment. Instead, it is brought out to define the extent of effort put into PMS testing in a particular case.

4.3.2 PMS installation

The existing underlying structure of the previous version [2] was utilized for the new PMS. This includes PMS cabinets and communication network, power supplies and circuitry, connection terminals, protection devices, and sensor systems for equipment transferred to the new system. Due to this, the PMS installation focuses mainly on the new components setup. The only modification made inside PMS cabinets was the installation of new I/O terminals and protection devices to interface with newly added sensor systems. Also, the cabling inside cabinets was modified, as some of the monitoring solutions created in the previous system were discontinued. However, the existing cables were reused to collect signals from new sensors. The location of the monitored production equipment and PMS hardware is shown on schematics in Appendix 3. The entire PMS circuitry is presented on schematics in Appendix 4. Finally, the pictures of modified cabinets are depicted in Appendix 5.

After rebuilding the electricity system, machines were powered from sockets hanging off cable trays, a common practice in the footwear industry for two reasons. One is to protect the cabling from possible impacts with trolleys used to move the products between workstations. Another reason is that the equipment has to be relocated from time to time, which could be complicated as the machinery is usually rather tightly packed together. Using such a cabling solution makes it possible to quickly disconnect the machine from the supply network and relocate it to another location. Therefore, the primary side of the current transformer must be connected before the socket, which powers the specific monitored unit, but after the distribution from the mainline supplying a group of machines. Considering those requirements, a suitable location was selected at the cable tray (Figure 4.7), to which the current transformers were fastened using special mounting brackets included in the package.

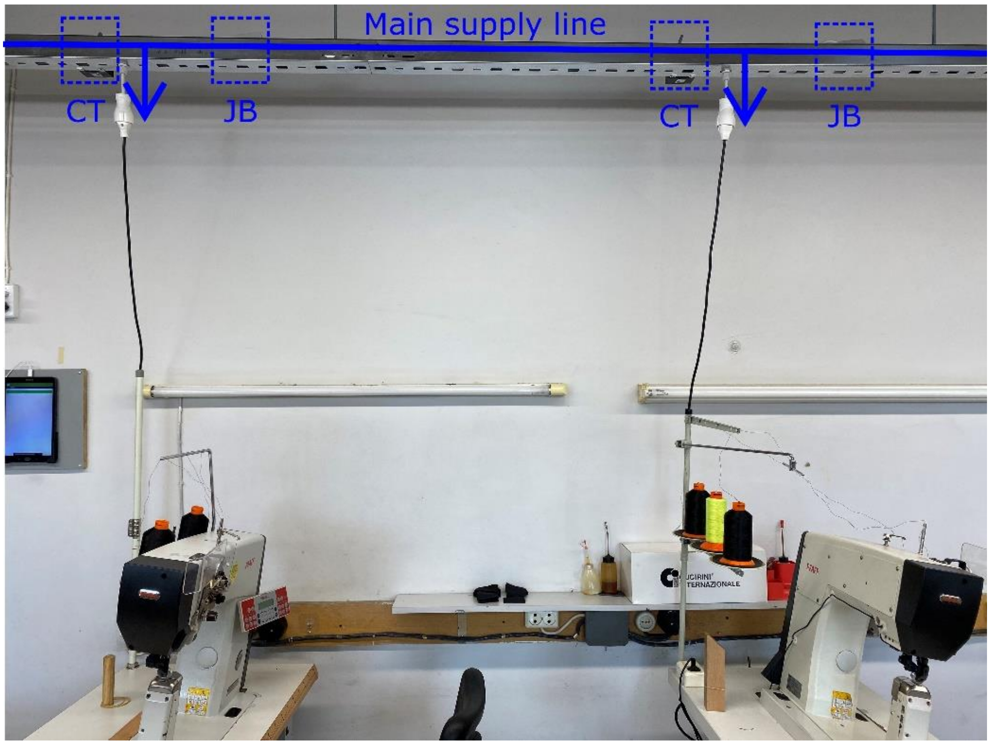


Figure 4.7. Current transformer installation at sewing machine (CT – current transformer, JB – junction box)

The phase conductor of the main supply line is routed from the junction box to one of the current transformer's primary terminals. From the other terminal, the phase conductor is routed back to the junction box from where it leads to the socket powering the machine. The secondary terminals of the current transformer are connected to a signal cable routed to the PMS cabinet for current measurement via terminal EL3446. The circuitry is protected on the primary side with properly dimensioned protection devices in the electrical cabinet accounting for electrical distribution network architecture and current ratings of measurement hardware. It is vital to avoid the open operation of the transformer's secondary side under load as it could induce high voltages on the secondary terminals. All the electrical connections were made with rated terminals and conductor sizes, accounting for the machine's current rating. The cable ends with a single layer of isolation were isolated with electrical tape and heat-shrinkable tube. A principle schematic of single current transformer circuitry is presented in Figure 4.8. In total, 17 of those current transformer setups were installed at the test platform.

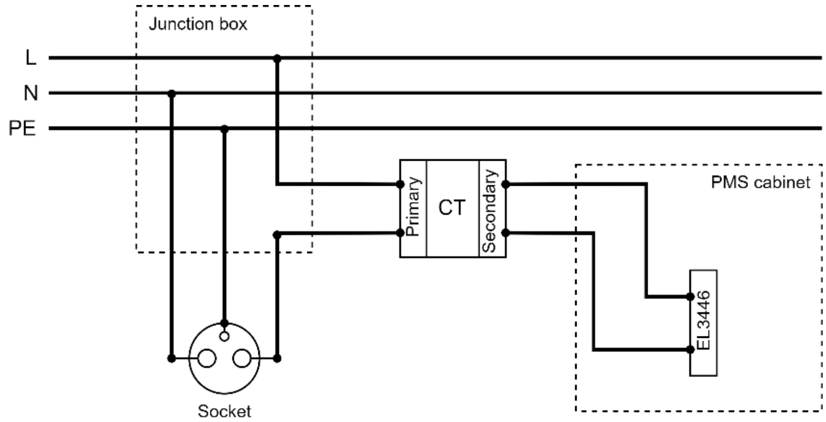


Figure 4.8. Principle schematic of current transformer measurement circuitry

Installation-wise, similar was the current transformer for monitoring the facility's electricity supply. The current measurement signal from three phases is collected via a ring-type current transformer connected around phase conductors in the main electrical cabinet. The transformer is located after the main switch and protection devices to leave the possibility for de-energizing the primary side if modification or maintenance has to be performed in transformer circuitry. An additional three-phase automatic protection switch was installed for acquiring voltage signals, from where the voltage signals were routed to the EL3443 terminal voltage inputs. The circuitry principle is similar to the one presented in Figure 4.3.

The next segment of sensors installed at the test platform was environmental sensors. Two multifunctional indoor environment sensors were installed, one per floor. The placement of sensors was selected according to the guidelines given in the manufacturer's user guide [51]. The installation height from the floor was around 1,5 meters to get an adequate reading of carbon dioxide affecting persons in the room. The selected location was also evaluated for possible wind drafts to minimize disturbance in readings caused by moving air. The sensor's wiring was made according to the schematic given in Figure 4.9. The PMS cabinet's 24 V supply was used for the sensor supply. The positive supply line was equipped with fuse protection, having integrated switch functionality to allow switching sensor off if needed. The single-ended signal connections and analog signal ground were routed to the terminal EL3064 in the PMS cabinet.

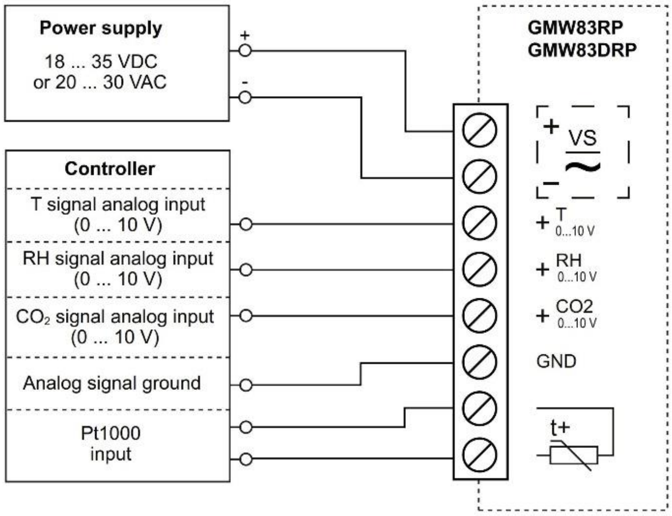


Figure 4.9. Wiring diagram of Vaisala GMW83RP environment sensor [51]

In order to capture accurate outdoor temperature, the RTD element had to be installed in a location where it is not disturbed by heat from the sun or dissipation from the building. The cable connected to RTD was routed through a wall into the junction box where the E2163 transmitter was situated. The conventional 4-20 mA signal was read from the transmitter output by connecting the signal cable to the EL3022 terminal in the PMS cabinet. As the selected transmitter can be used for various measurements, it had to be configured with a specific RTD type and required measurement range. The configuring was conducted through a USB interface with a PC using special software provided by the manufacturer [52].

Signal cable selection and its quality of installation are the two most critical aspects of achieving the needed reliability at the physical signal level by using wire-based communication methods. Since the industrial environment is typically tightly packed with various electrical equipment and cabling, it is essential to minimize the possibility of corrupting the signal due to disturbances caused by electromagnetic fields. Therefore, the already started approach in the first version of PMS [2] is continued here by using only shielded signal cables. This helps to ensure immunity even if it is impossible to separate the signal cables from power cabling. However, suppose the signal cable must be installed close to the power cables. In that case, it is crucial to apply necessary preventive measures, for example, cable separators in cable trays and installing crossing cables at only right angles. All the signal cables are selected from the ÖPVC-OZ-CY series produced by TKD Kabel [53]. Two-, four- and seven-core cables were used depending on the connectable sensor type.

4.3.3 Financial cost estimation

The financial cost estimation is made on an example of a particular PMS setup installed at the test platform company, including hardware from the previous system. Since the current solution is a pilot run of the PMS and includes many development hours, it is not adequate to count them into the financial evaluation of the PMS as a product. Furthermore, the cost of development, especially software development, depends on the number of standardized functions applicable for reuse in other systems, which is also set as a target to tackle during this development. Therefore, the costing is presented only for the main hardware and software components required to build the system. In order to perceive the overall system costing, it is necessary to consider the extent of the system and the amount of monitored equipment and parameters.

First and foremost, together with the newly added and the ones continued from the previous PMS, 30 sensor systems are present. Out of those, 26 sensor systems are applied for production equipment monitoring, three for the environment, and one for facility monitoring. With 30 sensor systems, 39 physical signals are acquired from the field level. As the monitoring solutions are developed so that a single sensor can be used to monitor multiple parameters on a single machine, the number of monitored parameters could be estimated at around 150. This includes monitoring all three fields, production, environment, and facility.

The total estimated cost of system components in summarized groups is presented in Table 4.2. The central part of system cost is hardware, from which the most significant part is sensor systems. Considering the quantities, the active infrared sensor system existing from previous PMS and indoor multifunctional environment sensors make the biggest contribution to this segment. The other devices, such as current measuring hardware, feature a much lower cost per monitored unit. The next biggest cost group is the control hardware, followed by the I/O terminals to interface with sensors. In the software field, piece-wise, the most expensive is the reporting software, which by system design could be optional.

Table 4.2. Estimated cost of software and hardware components

Parameter	Value
Hardware	
Management level PC	620 EUR
Control hardware (including PLC, I/O couplers and junctions)	1 265 EUR
I/O terminals	1 085 EUR
Sensor systems	1 841 EUR
Cabinets, power supplies, terminals and protection devices	468 EUR
Cables	480 EUR
installations materials	320 EUR
Total hardware cost	**6 079 EUR**
Software	
Reporting software	960 EUR
PLC licenses (including visualization)	1010 EUR
Total software cost	**1 970 EUR**
Total hardware and software cost	**8 049 EUR**

Considering the cost of components and adding an estimated cost for installation and software configuration for a fully developed system will raise the total cost by over 10 000 EUR. This makes the system quite an expensive investment. However, it should be noted that the system is a one-time investment, and cost-effectiveness will be achieved in the long run. In order to compare it with service-type solutions, suppose an example fee of 10 EUR per monitored unit, which is commonly a lot higher. This results in 3120 EUR payment in a year for 26 units of equipment. Thus, the system will benefit in cost in approximately four years.

Moreover, with more extensive systems containing more monitored units, the cost for a single node will be less as the base structure hardware will not change much. Similarly, the cost of control hardware (e.g., PLC) and installation materials can be optimized for a smaller system. From a company's perspective, the biggest downside is the decision-making on whether to apply the system and if it suits the needs. If it does, it is possible to achieve cost-effectiveness in the long run.

5. CONTROL SYSTEM

5.1 PLC program architecture and resources

5.1.1 PLC project- and variables structure

The most extensive part of software development is made in PLC programming, as most of the system's functionality is carried out there. One of the essential aspects is the planning of program structure and variables. The overall principle of the PMS is very much related to specific monitored hardware units. Thus, it is crucial to organize the software accordingly using object-oriented programming principles. As the name implies, the method imposes software creation around objects rather than software functions and logic. From the context of the PMS, the functions related to the monitoring of specific equipment should be combined into a single logical software unit. This enhances standardization and grants a better overview of the program.

In order to leverage mentioned approach, the main program calling out the instances of function blocks is created in FBD (Function Block Diagram) language, where each separate block is intended for single monitored equipment or sensor. In addition to a good program overview, it simplifies the management of the variables linked to function block instances. An example of a section from the main program that calls out two instances of the same function block for monitoring two separate units of production equipment is given in Figure 5.1. The inputs or input-outputs used for monitoring are connected to the function block from the left. The output parameters-set carrying the monitoring data is present on the right.

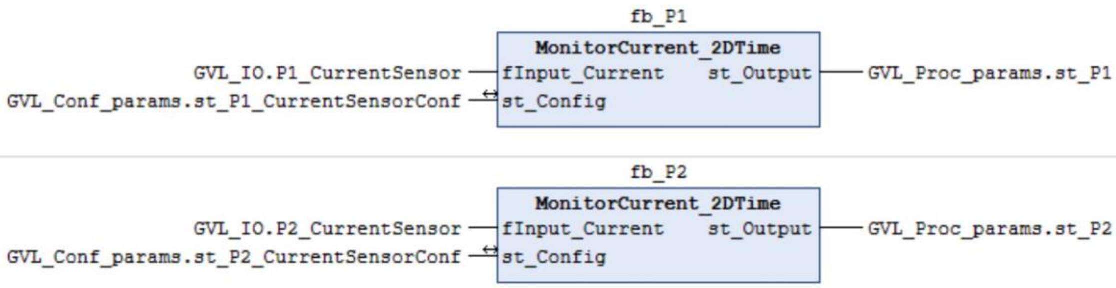


Figure 5.1. Section of main program composed in FBD language calling out two instances of a function block

The function blocks themselves are written in ST (Structured Text), as it provides more flexibility than other languages. An object named method is used for further standardization inside the function block. Methods are similar to functions as they do not contain memory and are re-initialized at each call. However, they can access the variables of the function block they are assigned. By employing methods, it is possible to create standardized smaller code sections and call them out by method name in the function block. This kind of approach has two advantages. First, the methods can be reused in other function blocks, such as a trivial method for filling an array buffer (Figure 5.2). Secondly, it advances the overview as bigger logical code sections serving a dedicated purpose can be combined under a single line of code in the function block.

```
// Call timer
fb_TonTimerWriteToArray();

// Fill buffer at first cycle
IF bFillBufferRequested THEN
    FillBuffer();
END_IF

// Write to buffer and calculate std.dev.
IF fb_TonTimerWriteToArray.Q THEN
    // Write values to array
    WriteToStdDevBuffer(fInput := fInput_Current);
```

```
FOR nIndex := 1 TO 30 BY 1 DO
    arrBuffer_InputValues[nIndex] := fInput_Current;
END_FOR;
```

Figure 5.2. Principle example of method usage inside a function block for structuring the code

In order to manage and organize variables, user-defined enumerations and structures are used. Enumerations help make the code tracking easier as the value of the created data type is presented through user-defined keywords rather than numeric values. Structures contain different variables usually grouped based on their logical usage. An example of such a structure containing input configuration data for current-based monitoring is given in Appendix 6. Structures must be composed for a group of monitoring types with a certain amount of universality to apply them in different scenarios without creating a new one. Those structures for each designated monitoring unit are declared in GVLs (Global Variable List), from where they can be linked to the specific function block in the main program. The structures and variables are divided into four GVLs based on their origin or usage. For example, all the output parameter structures are declared in a single dedicated GVL.

Another essential aspect of the PLC project structuring is the tasks under which the separate programs are attached. Tasks allow management of subordinate programs' scheduling and prioritization, determining their computational resource usage and execution. For example, the main program for monitoring and other programs (e.g., communication driver) should be intentionally separated for effective and reliable system execution. This allows for running them in separate tasks and managing their CPU time prioritization as needed. Furthermore, as the PLC features a 4-core CPU, it is possible to isolate tasks on separate cores to guarantee continuous parallel execution.

However, the need for this and the exact configuration is case-specific and is dependent on the volume of programs executed.

5.1.2 Communication drivers

PMS algorithms execution on PLC requires various supportive functions providing the necessary services. One crucial segment is communication drivers to communicate with instances located in remote devices. The drivers for PMS can be divided into two distinct groups based on the data transmitting principles. One type of a driver is characterized by the need to continuously log data in use cases when consistent data logging is required and the receiver side is available. The other type of driver dedicated to database communication is for cases if periodic data logging is needed or the destination instance may not be accessible at all times.

A single instance of continuous type communication driver is applied for production monitoring data transmission to the reporting software located at a remote PC. The decision for applying such a driver type is that consistent data gives better insight into production parameters, and the system design assumes the readiness of the destination device during the workday. The driver is realized using Modbus TCP/IP as it is a widespread and robust solution for industrial automation communication over Ethernet. The driver in the PLC project is a separate program established as a Modbus slave from functions present in the TwinCAT Modbus TCP library [54]. The program is written to continuously write parameters to holding registers from where they can be read by reporting software Modbus driver acting as a master. The Modbus driver program is allocated to a separate task to manage the prioritization and scheduling separately from other system parts to guarantee the reliable communication.

The other type of driver, intended for database communication, is present in a slightly different form in multiple parts of the PLC project. Thanks to periodical data transmission and more abstract relation with destination instance, the separate PMS functions (e.g., maintenance management) can be assigned with their own driver. This helps avoid a single driver with overly complicated logic to provide services for all logging needs and contributes to a better-structured solution. Regardless of the objective, all the drivers are composed as function blocks with similar tools provided by the TwinCAT database function [55]. The driver features all necessary tools to communicate with a remote database, for which in the system built during this work, the MS SQL Express is installed on a management-level PC.

The database management is performed using the TwinCAT database server function. The function provides multiple modes with different levels of complexity depending on the required functionality. For example, the simplest mode can be used for pure data logging, such as environment and facility daily parameters. In that case, the log tables are configured during development, and values are logged into them using simple programmed commands in runtime. On the other hand, suppose more advanced methods are required, for example, in maintenance management. In that case, the SQL Expert mode can be utilized, allowing native SQL commands for data insertion and access through programmed instructions. Furthermore, because in a particular system, the database server is located in a remote device, the write procedures are equipped with buffering mechanism for occasions where the remote device is not reachable (Figure 5.3). This helps to guarantee reliable data insertion into the database. However, this does not guarantee data reading. These occasions should be handled with additional methods and logic, but they are not in the current work's scope.

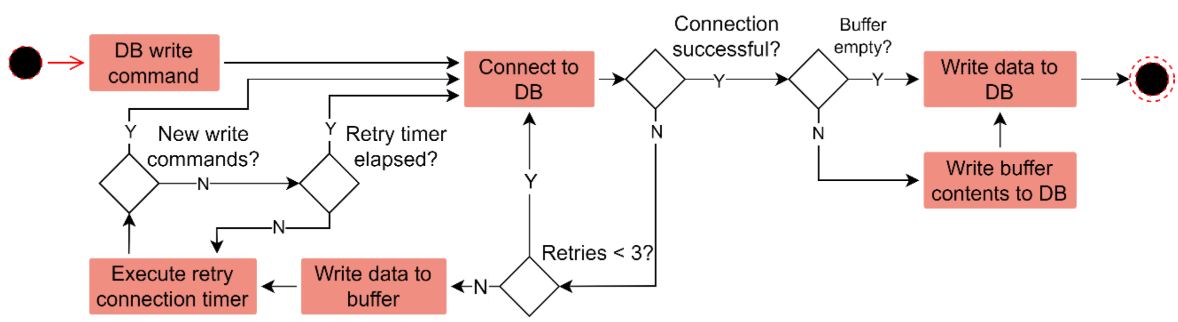


Figure 5.3. Buffering logic execution for write procedures

5.2 Algorithms design and implementation

5.2.1 Production monitoring algorithms

The development of production monitoring algorithms on the PLC can be logically divided into separate parts (Figure 5.4). In terms of processing logic, the most crucial part is within the function block, driving the monitoring of a specific equipment unit. In order to apply similar monitoring functions with different types of physical input signals, there is a need for a so-called medium. The main idea behind a separate medium is to increase universality by pre-processing input signals with various types and characteristics into a suitable form for monitoring functions. This could contain simple discrete logic or more advanced calculations and filtering. By applying such a concept, it is possible to separate the monitoring functions from the concrete physical signal.

Thus, ideally, the monitoring functions could be adapted to inputs with various types and characteristics to some extent.

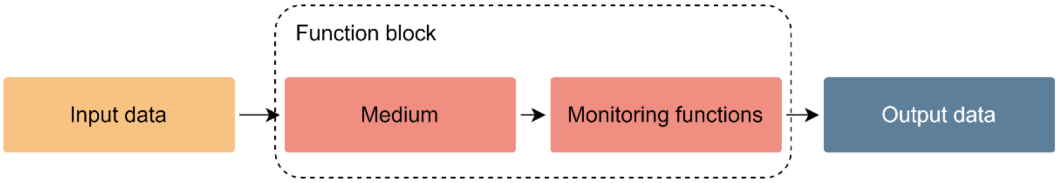


Figure 5.4. Logical parts of the monitoring algorithms

As the final goal is to provide a particular set of output parameters depicted in Figure 3.1, the creation of algorithms started from achieving needed monitoring functions. The first significant group is time-based functions, which are realized through different usage-time counters and statistical calculations. They can be executed by acquiring a Boolean value (TRUE or FALSE) from the medium, which has been processed into meaningful form to describe the current status of monitored equipment. The next group of functions is associated with quantity- and cycle-based monitoring. Depending on the signal type, those functions are generally easier to implement using various counters and discrete logic. However, the parameters such as quantity/cycles in an hour or others still require additional time data inputs. On the medium side, those functions usually do not require extensive pre-processing as the physical input signal is valid as a direct input. The last, status-based functions, mostly use parameters produced by medium or straight from the physical input.

After achieving all the functions to produce parameters presented in Figure 3.1, the mediums for physical input signal pre-processing are developed. One of the most notable, compiled during the work, is analog signal pre-processing to obtain the standard deviation of the signal in time to offer more robust monitoring. The concept proposed in chapter 3.4.2 is solved by saving raw analog input values into a ring buffer with configurable interval and length in time. By calculating the standard deviation of the buffer, it is possible to determine whether the machine is currently performing practical work or not. The only assumption is that the analog signal has variations during work mode or that the change from standby to work mode is identifiable. In addition to applied logical operations and calculations, the medium should be able to provide means for filtering. For example, work time monitoring requires filtering to neglect shorter pauses between working states if needed (Figure 5.5). The filtering is also beneficial when applied for monitoring with pulsive digital input (e.g., detecting continuously moving metal object on the production machine with an inductive sensor) to avoid logic fluctuations on the monitoring functions level.

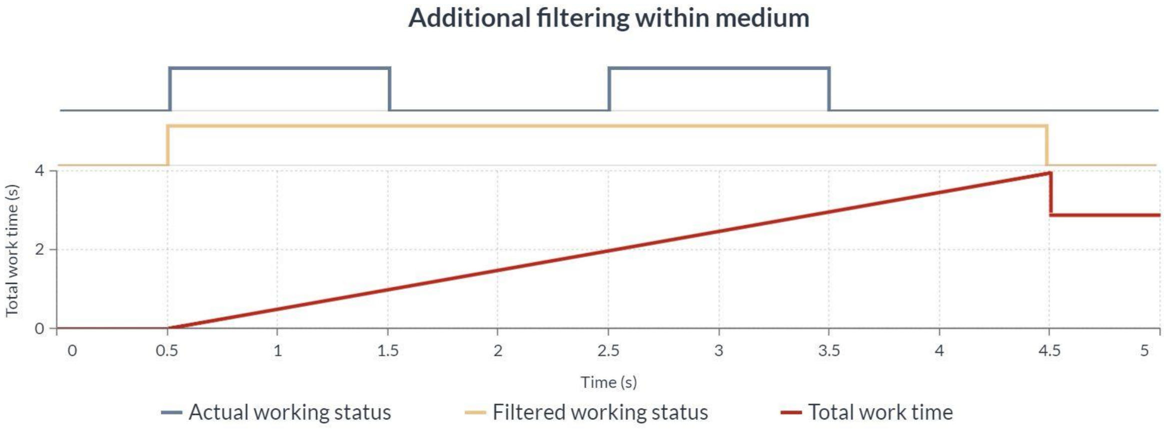


Figure 5.5. Principle example of work time monitoring with applied 1 s filtering (note subtraction of 1 s from total work time if there is no actual working status for 1 s)

As a result, 13 different monitoring functions and five different medium types were developed for production monitoring purposes. Those were designed as standardized building blocks, of which five monitoring algorithms were composed for the system installed during this work. Furthermore, to drive all the administrational actions of the system, several system execution function blocks were composed. Examples of such could be a function block for managing the timing and triggering of monitoring actions or the configuration manager helping to conduct monitoring parameters configuring across the system. The high-level structure diagrams of production monitoring algorithms can be seen in Appendix 7. However, it is essential to mention that structure diagrams do not directly reflect the programmed algorithms due to their extent but rather the dependencies between functions and data population.

In Figure A7.1, an example of an algorithm used for sewing machine monitoring is shown with electrical current as input. This illustrates the advantage of separated medium with filtering as algorithms created for sewing machines with other input types deploy the same functions-set. The only difference comes in medium containing different signal processing and filtering. Figure A7.2 depicts the principal structure of the stamping machine algorithm using the existing end switch signal as input. The two-input algorithm for time- and products monitoring at the assembly line is shown in Figure A7.3. In the case of the assembly line, additional filtering in the medium is not required as both inputs are relevant in raw form.

After composing a single unit of all the previously described algorithms, applying testing methods by emulating the physical- and software-level signals as realistically as possible is essential. This helps to guarantee that all the algorithm parts are working as intended before commissioning them in the physically installed system. Furthermore, as monitoring functions tend to include time operations, they are validated by conducting repetitive tests in longer fixed time frames. Otherwise, the minor timing errors could affect the parameters during longer execution in run time.

5.2.2 Environment and facility monitoring algorithms

The environment and facility monitoring algorithms are less variant in terms of different functions as the monitored parameters' behavior does not differ from application to application. Therefore, the segment could be covered with one standardized set of functions applicable in many systems. In addition to the physical input signal scaling and averaging functions, the environment monitoring signals are equipped with fault detection. The single-output outdoor temperature measuring allows to detect only the inaccurate or missing signal/connection. In contrast, the combined indoor sensors are placed with power failure detection if all three signals are below the critical range. Additionally, the algorithms are supplemented with functionality to calculate the average parameter value across the day for reporting purposes to see more extended parameter trends. Those values from various environment and facility monitoring parameters are written to the SQL database through a dedicated driver.

For the electricity supply monitoring, most of the processing is already integrated by the vendor and is achievable with the correct configuration of the measurement terminal. Therefore, the electrical supply monitoring function block features mostly different value conversions into relevant units. On top of that, a method had to be developed to monitor the consumed electrical energy in time. One option was to save the power consumption profile through time and calculate its integral. Another alternative was to make a simplification and iteratively summarize the average power consumption of a known short period (Figure 5.6). The second method is more efficient in allocated memory and computational power, so it was chosen for implementation. However, the method's accuracy must be validated after a certain test period for which the electrical transmission system operator's provided data can be used as a reference.

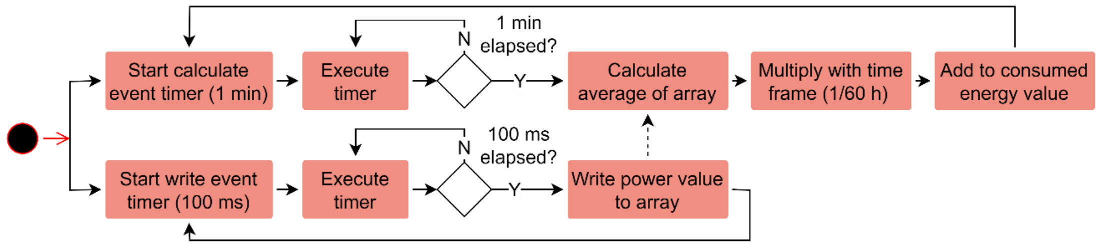


Figure 5.6. Structural schematic of electrical energy consumption measuring principle with example values

5.2.3 Maintenance management algorithms

The implementation of maintenance management is mainly built around different database access methods, requiring both writing and reading of data. For this purpose, a separate database driver is allocated for exchanging maintenance management data centrally. The functions of the maintenance management concept proposed in chapter 3.2.3 in Figure 3.3 can be divided into two groups. The usage-based functions are executed periodically after each workday to conduct regular preventive maintenance if the interval is reached. The condition-based group is executed continuously through the workday to determine abnormalities and react to them. Despite that, they are still embedded into a single function block. The usage-based function is called out only via trigger after the end of the workday or on user confirmation for performed maintenance action.

The usage-based functions are built on two separate tables in the database. The first table is used as a buffer to log the current state and description of the running maintenance interval. At a trigger event, the algorithm summarizes the usage data from the current day with the data from the database and stores it into the table using the SQL update command. The multiple components tracking on a single machine requires accordingly configured database tables and PLC structures (in current configuration maximum is 10). Data from a specific machine is logged into the database as a single row with an identification key. The other table is used to keep the conducted maintenance actions log. The execution principle of usage-based periodical data updating and user confirmation of maintenance action is brought in Appendix 8. The user confirmation represents the logic if maintenance action is performed on a single component and the usage data of other components in the buffer table remains the same.

The condition-based maintenance functions are equipped with a separate table to log all the events and user confirmations using unacknowledged and acknowledged principles. Contrary to the usage-based functions where the maintenance interval description (e.g., interval length in hours) is included in the buffer table, the condition-based functions store the preset conditions in PLC persistent memory. This is because condition-based functions use relatively simple conditions for triggering the action, such as analog signal boundary values. Thus, they can be stored in the PLC in a smaller scale system. However, an additional database table can be deployed for storing the configuration for more extensive systems with a larger number of production machines.

Implementation of condition-based maintenance functions is generally more straightforward as the algorithm is responsible for only triggering notifications and logging events. However, more complicated logic is needed if abnormal patterns in the signal have to be detected. An example of such could be a multi-timer logic to detect miss-placed product counting sensor from the digital input characteristic in the current application. The principle schematic of the execution of the condition-based function is visualized in Figure 5.7. A single cycle of critical electrical current consumption tracking is shown in a particular example. The algorithm uses an alarm bit and timer combination to avoid flickering of notification and log triggering.

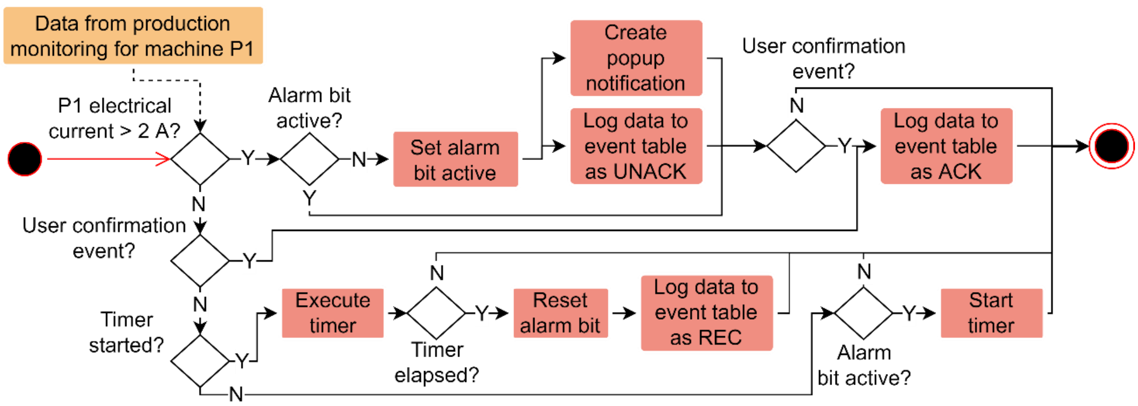


Figure 5.7. Example of a condition-based maintenance monitoring function to detect and notify the user about critical current consumption (UNACK – unacknowledged, ACK – acknowledged, REC - recovered)

Due to maintenance management high dependency on database communication, the concept had to be thoroughly tested before deployment by simulating a similar scenario with a remote database. The system installed during this work features usage-based maintenance management on all the production equipment integrated into the PMS. The sewing machines are applied with time-based maintenance monitoring. On stamping machines, the number of work cycles is used. The assembly line is equipped with the combined version featuring work time and produced products as both inputs are relevant for monitoring the maintenance requirements of specific components. Condition-based maintenance is applied to detect various problems on production machines, such as overcurrent on a sewing machine, and issues within PMS itself, such as miss-placed product counting sensor detected by abnormal discrete signal behavior.

5.2.4 Prediction algorithm

Predicting the productiveness with ML is one of the most comprehensive functionalities to be developed into PMS. Due to its high complexity, it was divided down into smaller parts that can be developed and deployed step-by-step. The first step is to create means to acquire and store data needed for ML model training. The second step is to achieve the actual functionality by training and validating the model using different mathematical methods. The third and final step is fully integrating the functionality into the PMS. Due to the time scope of current work and inadequate amount of data from the previous PMS, the actual implementation of predicting functionality was not achievable. However, the work practically resolved the first step of the process to form a solid basis for the next steps. Moreover, the proposals were made for the following steps to be developed in the future.

The first step of achieving the prediction functionality has three crucial parts, data acquisition, storage, and parameter selection. The storage part at the test platform company is realized via the already implemented external database solution to maintain a unified line in the control system supportive functions and resources. Furthermore, the SQL database is a standard tool for data storing, providing convenient access to various programs and frameworks to be used later for data processing during ML model training. Therefore, a dedicated table in the database and a driver function block in the PLC project were created, tailored for prediction functionality data storing and handling.

The PMS functions already cover the data acquisition part. However, the most crucial aspect contributing to the results of ML-based prediction is relevant input parameters selection and the way they are presented, also called feature engineering. Due to the early prototype phase of the functionality development, it is vital to consider which parameters to log for future development. Furthermore, as the choice of collected parameters in the current application is mainly free until the extent of physically acquirable inputs and the data generated from them, it is reasonable to log all the parameters directly or indirectly related to the estimated output value. Therefore, relying on the approach proposed in chapter 3.2.4 during PMS concept design, parameters from three fields, production, environment, and facility, were considered.

The production monitoring parameters have the most direct effect on the production output. Hence, the main monitored parameter (e.g., worked time) from all the machines is the most valuable source of information. The environment parameters have an indirect affect through personnel, and facility data could feature both direct and indirect effects, for example, through consumed electrical energy. In addition to the parameter groups proposed in the PMS design phase, the date data is also added, specifically, the day of the week in numeric form, as it may reflect the productiveness. The others, for example, month, can be derived later from the record date. The whole set of logged parameters from the particular system in a summarized form is shown in Table 5.1. In order to estimate the production for the next day(s), all the logged parameters are accumulated and averaged through the workday, except day of the week.

Table 5.1. Parameters logged for prediction functionality development

Data group	**Parameter**	**Type**	**Quantity**
Production monitoring	Worked minutes	Sum	22
	Performed cycles	Sum	3
	Produced products	Sum	1
Environment monitoring	Indoor temperature	Average	2
	Indoor humidity	Average	2
	Indoor CO2	Average	2
	Outdoor temperature	Average	1
Facility monitoring	Electrical energy consumption	Sum	1
Date data	Day of the week	Value	1
Total			35

The second phase is dedicated to acquiring the ML model for which there are numerous options. However, the chosen one has to be supported by the PLC vendor' ML inference function to integrate functionality into the control level PLC later. Currently, the ML inference engine provides support for three models suitable for regression tasks, but more will be added as stated in the manual [56]. Those models are Support Vector Machine (SVM), Random Forest, and Multi-Layer Perceptron (MLP, generally ANN). Each of them has different characteristics and implementation principles. For example, the Random Forest is less sensitive to configurations during model design than MLP, and the model training is generally faster. However, the exact model type producing the best results must be determined during actual model development.

The achieved results with a specific model are dependent on the input parameters selection, named attributes. Those can be selected by manually determining the highest correlating parameters or using automatic attribute selection methods. In order to provide insight into possible attributes, two different scenarios are proposed here on the example of predicting Thursday's production on Wednesday. For most productions, the performed amount of work at the beginning of the process does not necessarily mean a concrete outcome in some next day. Therefore, to capture trends, data from only the current day is probably not sufficient to predict the production outcome of the next day(s). Thus, one option is to use production monitoring data averaging, for example, across the last three days (Figure 5.8). Another and possibly more beneficial method would be to use lags, providing data from specifically selected days in the past. As shown in the lower graph in Figure 5.8, the current day (Wednesday), the day before (Tuesday), and the closest same day (last Thursday) are all selected as separate attributes.

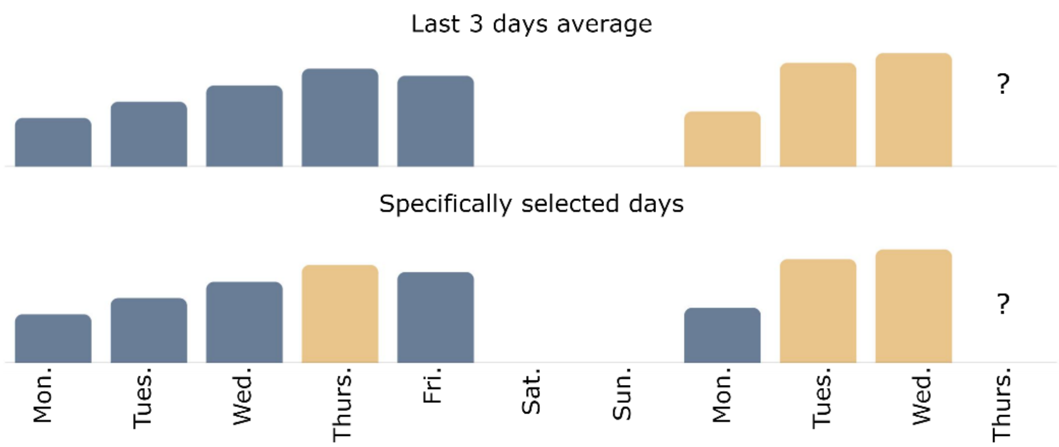


Figure 5.8. Comparison of data allocation for two types of attribute selection on the example of estimating production for Thursday (yellow – allocated data, blue – not used)

The last phase is integrating functionality into PMS if the received results are satisfactory. The trained ML model can be simply imported to the PLC project in ONNX (Open Neural Network Exchange) format during the initial testing. However, considering the functionality as a part of product type PMS in the future, it is not feasible to first collect data for an extended period and then apply the prediction function. Therefore, additional mechanisms should be developed to provide continuous learning of the model starting from system installation (Figure 5.9). As currently, the PLC environment does not provide any framework for model training, the periodical adjusting or retraining (depending on the model) should be conducted in the management level PC. The adjusted model can be automatically transferred to PLC and asynchronously uploaded during runtime. After making the prediction, the inputs and output of the model are saved to the database, from where they can be accessed during model training. The need for adjusting or retraining has to be verified based on model performance, for example, the accuracy of the last ten predictions, to avoid unnecessary changes in the model.

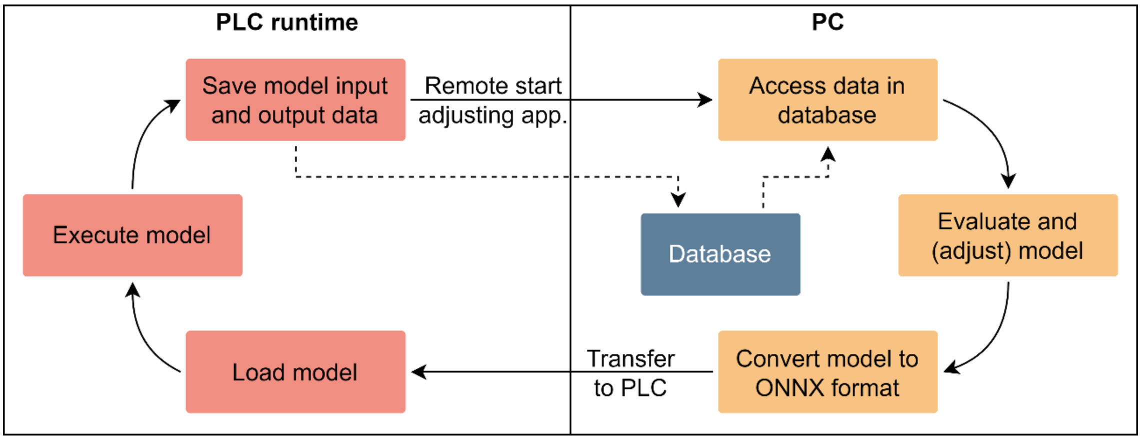


Figure 5.9. Proposal mechanism for continuously learning ML model execution

5.3 User interface

5.3.1 Visualization

The development of visualization based on TwinCAT HMI [48] started by creating the desktop base template on which all the pages are displayed. Considering the objective of providing flexible access to the PMS through various client devices, the visualization had to be created on dynamic principles to adapt to the client's screen resolution. Therefore, percentages and ratios are mainly used instead of pixels for defining the dimensions of areas and objects. Moreover, some objects have to be configured with width switch point on which they turn into mobile icons on smaller screens. This allows displaying the visualization on very different devices in similar form. The desktop base template is divided into header, menu, and display area from the top (Figure 5.10).

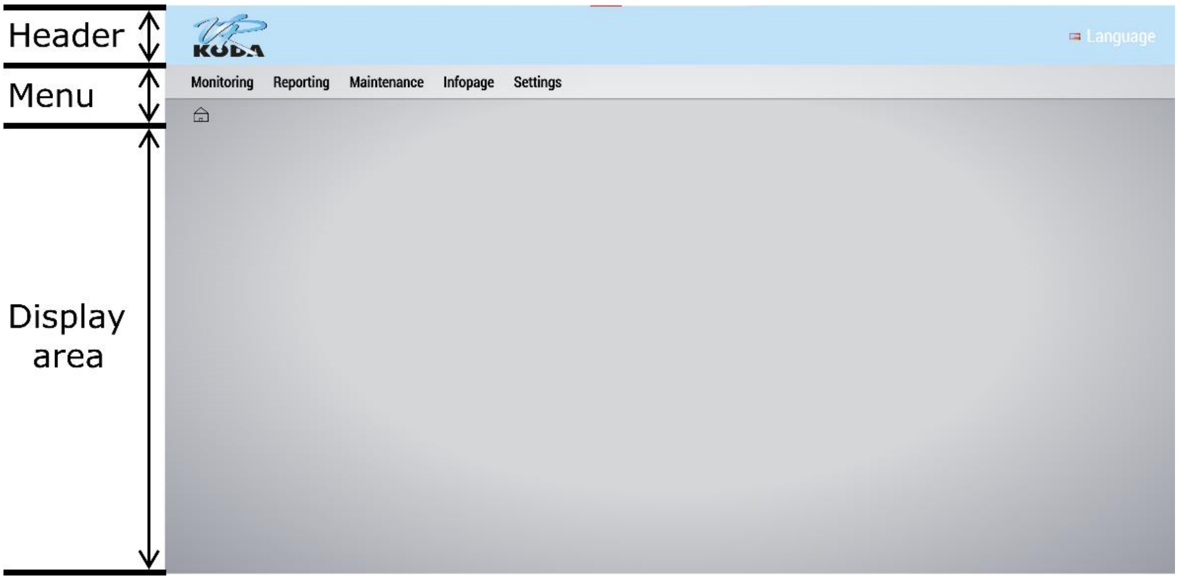


Figure 5.10. Areas of desktop base template

The header contains the company logo and localization selection, which is essential to implement from the first step of the development to create multilingual visualization. In this case, all the texts in the project are defined as keywords that are changed depending on the localization selection (in the current project, English, and Estonian). The menu features a drop-down construction with three levels allowing to distribute views based on the monitoring area or intended functionality. In addition, a navigation path tracker is added below the menu bar to pursue a good overview of the current location.

The next logical part of visualization is all the pages for displaying the contents. For standardization and minimal variance, only two types of page layout are used, blank pages for displaying larger graphics and pages with tabular sections for smaller contents. The main view of the system has to give an as good overview as possible in the self-explanatory form. This is realized by creating an isometric background of the actual production building layout onto which all the equipment is added (Appendix 9 Figure A9.1). The concept allows a more uniform representation for equipment symbols as the user obtains the relation through a geographical location. This, in turn, guarantees a less variegated view and higher reusability of symbols. It is crucial to divide the monitored sources based on their importance. Primary information such as production equipment has changing color attributes, and secondary ones such as environment parameters have a constant blue color scheme.

The production equipment on the main view is depicted with rectangles created as user controls with embedded logic for visualizing various states. The symbols are created in various sizes depending on the number of primary parameters to display. An example of a single primary parameter (work time) symbol is shown in Figure 5.11. The symbol is equipped with configurable machine identification in the left upmost corner. The work time and normative time percentage calculation are included in the symbol's center. Different machine states are visualized through two attributes, fill and boundary color (Figure 5.11). The boundary colors visualize the machine's current state and maintenance notification. Fill colors describe the machine efficiency according to the primary monitored parameter (e.g., time, cycles, products) and user-defined levels.

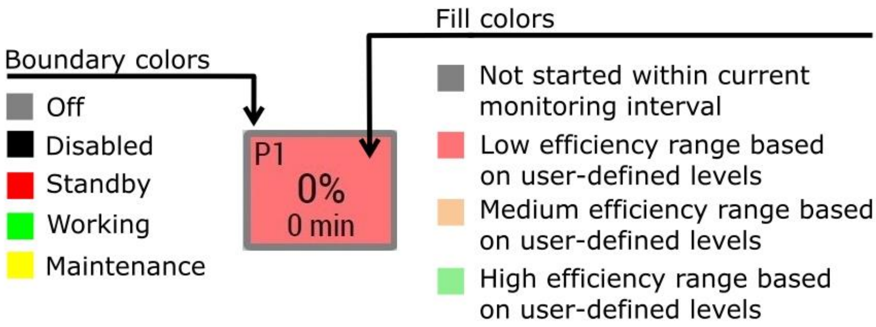


Figure 5.11. Color scheme of the equipment symbol

Detailed information regarding each production machine can be acquired by clicking on the symbol, which opens a three-page popup divided into main-, graph- and configuration views. An example of all three views for current-based monitoring is shown in Appendix 9, Figure A9.2-A9.4. The main view of the popup presents all the numeric and status information of the machine. In addition, the main view includes the raw value of the input used for monitoring and the status of monitoring functions input (raw status either performing work or not). This allows verifying the algorithm's correctness based on visual observations if the actual work overlaps the algorithm status. For example, in Figure A9.2 (Appendix 9), the raw status identification can be seen on the right bottom corner with numeric current consumption value and green fill color. The graph view displays the line chart of the essential parameters. Finally, the configuration view allows changing the monitoring configuration of the specific machine.

Besides the main view, the production monitoring segment is equipped with various other pages grouping equipment by type (e.g., sewing- or stamping machine) or location (e.g., floor, building section). However, the basic principles of visualizing the elements remain the same. On top of displaying the environment and facility monitoring information in the main view, more thorough details can be acquired from their dedicated views. These include numeric values, statuses, and trending functionality.

The facility monitoring group also has an extension to the local heat management system in a particular solution. This is realized by launching the system's origin web interface from the PMS visualization. A similar principle is used to open the web interface for reporting. The only segment not included in the visualization during this work is the maintenance management dedicated views, as the interface requires additional development and testing prior to publishing into the runtime system. Some examples of different views are presented in Appendix 9, Figure A9.5-A9.7.

The following important subject for system execution and monitoring is all sorts of settings affecting the system behavior and monitoring. For this purpose, two separate views are created (Appendix 9, Figure A9.8-A9.9). The system settings view provides the user with general visualization preferences such as theme and monitoring options such as scheduling. The monitoring settings view, which requires administrational rights for access, unlocks more specific configurations affecting the system monitoring behavior for various monitoring groups. The page is equipped with a configuration panel for every type of monitored production equipment, allowing changes in monitoring algorithms across all the equipment. This is extremely important during system commissioning, as configuring a network of devices may be time-consuming. Leveraging this approach, it is possible to first make a so-called broadcast configuration from the monitoring settings page and more minor adjustments using a dedicated configuration structure through the individual popups in the main view (Figure 5.12).

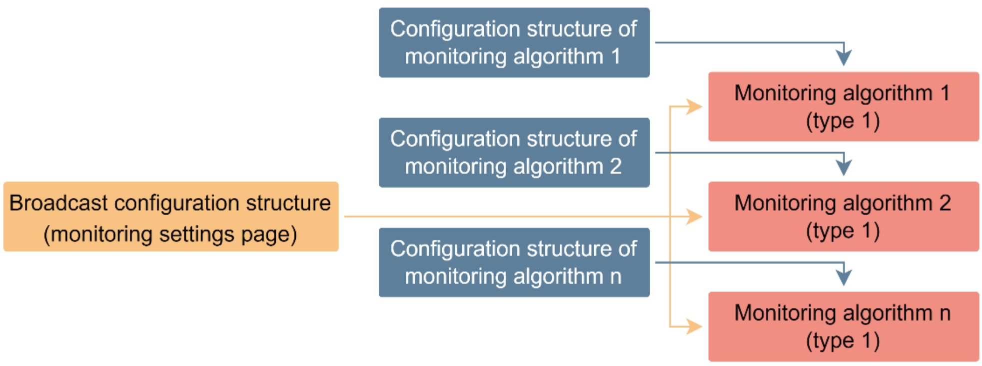


Figure 5.12. Principle of broadcast- and dedicated configuration of monitoring algorithms

Linking variables between visualization and the PLC project plays an essential role in such a system. Therefore, the data presentation principles on visualization should be considered during PLC data structures creation. Mapping variables between two parties in the current system is straightforward as the visualization platform was intentionally selected from the PLC vendor. Nevertheless, organizing variables into logical groups for usage in the PLC program and visualization highly determines the integration time. Due to this, the variables were divided into data structures such as user configuration- or process data structure. This approach reduces integration time as all the symbols and popups are created in template form. For example, suppose a new production machine is integrated into the system. In this case, the template symbol and popup are added, and three primary structures are linked to them after mapping. Furthermore, using the same data structures helps keep high standardization across two projects.

5.3.2 Reporting

The new system's reporting functionality is even more significant considering the widened monitoring areas. The chosen Dream Report software [49] is designed to automate the time-demanding reports generation and bring them to the user as conveniently as possible. The software offers numerous drivers for connecting with all sorts of data sources. Depending on the information source, live or historical data, the Dream Report is also responsible for handling the data logging. The software provides an environment and statistical tools to design reports based on the application's needs. These reports are then automatically generated by the service or on-demand by the user with the data from Dream Report handled database or other historical data sources.

The basis of the reporting project is transferred from the previous PMS, mainly due to the verified value addition over an extended testing period. In order to adapt to the new system, multiple fundamental changes have been made in favor of offering more value and flexibility. The data logging and reports scheduling were fixed with a previous system configuration. The main objective of the rework is to make the report's scheduling and timespan dependent on the user configurations in PMS visualization (start and end of the workday). Furthermore, the development targeted to make on-demand reporting more convenient by applying web-based reporting realized on software integrated web interface.

The principle concept describing the high-level relations between different parties in the current system from the perspective of reporting software is given in Figure 5.13. The production monitoring data logging is performed through Modbus TCP/IP driver. The driver's registers mapping is aligned with the new communication driver in the PLC program to log all the newly allocated registers. The logger studio, responsible for real-time values logging, is reconfigured to log on condition using a trigger from the PLC. This allows linking the logging control to the PMS so that the user's scheduling changes also affect the data logging in the reporting service. Finally, the environment and facility data are imported from an external database using ODBC (Open Database Connectivity) driver for historical values [57]. Connecting to the database via ODBC allows to select relevant tables for the data and parse them into Dream Report data items. Usage of separate drivers is not the most beneficial. However, as stated in the PLC communication drivers chapter, the main reason motivating such an approach relies on the fact that reporting software may not be available at all times. Furthermore, from the perspective of reporting, logging the averaged and accumulated parameters once a day is sufficient to give an overview of environmental and facility data.

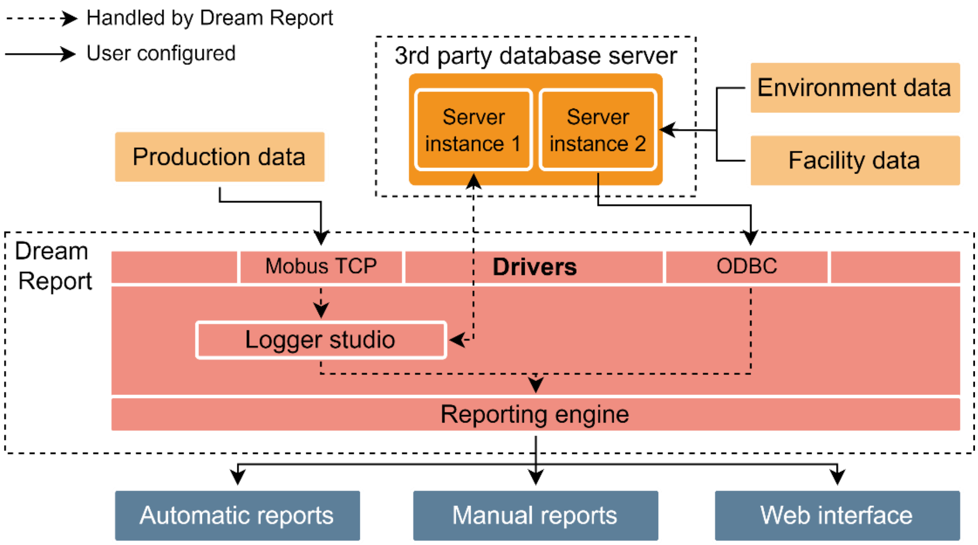


Figure 5.13. Structural overview of the reporting software and related parties

The generation of production monitoring reports is linked to a PLC-controlled parameter, similar to logging control, to generate reports on defined events. The reports' timespan is manipulated in the same way with additional objects and Dream Report's native LUA scripting inside specific reports. The whole modified concept provides flexible reporting without requiring hardcoded configuration changes after changing the PMS monitoring timespan. The contents of production monitoring reports have been updated to reflect data from all the monitored production equipment on daily-, weekly- and monthly reports. Moreover, new reports are added where production equipment is grouped by type, such as stamping machines weekly report. An example of a daily production monitoring report can be seen in Appendix 10 and a weekly report in Appendix 11.

For the purpose of visualizing the environment and facility data, four additional reports have been created, two for each. As both monitoring areas are captured into the database with a resolution of one day, the reports are designed for longer periods of one month and one year to see more extended trends. The environmental data reports present daily average indoor parameters on a line chart. Besides this, minimum, maximum, and average values are included with corresponding dates on which they were recorded (only for minimum and maximum). The total daily electrical energy consumption is displayed on the facility monitoring reports to see energy consumption trends and summarized statistics. The reports include similar statistical functions as environmental ones and also the summarized consumption value to see the total consumption through the reporting period.

The on-demand reporting feature is realized by creating a dedicated web report accessible from software embedded web interface. An example of the report can be observed in Appendix 12. The underlying design principle is the simplicity to allow fast access to main production monitoring statistics for user-defined machines and timespan. The statistical table on the report contains summarized and average (if multiple days selected) values for work minutes, work cycles, and products produced. The interactive line chart gives a comparative overview of the monitored parameters' trends between selected equipment in time. This chart is beneficial for identifying pauses and stoppages during the workday. The bar graph on the bottom gives an illustrative overview of the total quantities performed or produced during the workday. As the dynamic selection of machines is implemented with expression data objects counted as items defining the software license cost, the maximum number of allowed selections is limited to six. However, as the report is intended for comparative and fast data access purposes, the possibility of adding all the machines is not relevant and critical.

SUMMARY

The objective of this thesis was to develop a Production Monitoring System (PMS) specifically for small and medium-sized enterprises. The solution aims to help capture production efficiency, machines' utilization, and the effort allocated by personnel. Despite many systems reaching the market in recent years, there are still shortcomings indicating the need for further development. The analysis of existing systems revealed distinct patterns, with the main concerns in high management requirements, expensive service type solutions, and technical aspects due to usage of non-industrial hardware. Therefore, as a result of the analysis, the main aims for the system design were set. The work presented further develops a system established in the bachelor's thesis [2], relying on industrial automation principles. However, this time, a more standardized and systematic approach was taken to develop a system as a product applicable in different industries. Furthermore, the scope of system functionalities was widened to provide better insight into the company's operations.

Based on the aims set for the system, the PMS concept was designed, forming the basis for technical development. The system's requirements have been set from the product perspective, and also accounting for the needs of the test platform company. The functionalities of the system could be divided into four interrelated categories. The primary is production monitoring with various functions to cover the monitoring needs. The environment and facility monitoring provide additional information of the production environment and facility-related parameters. Maintenance management is a natural addition to PMS as the information related to equipment usage is already present from the production monitoring. Besides monitoring functions, the system concept introduces a production prediction function to estimate production outcome. The most significant structural change affects the software as most actions within the new system are concentrated in the control level PLC (Programmable Logic Controller). The biggest contribution to this is a new approach to visualization with the server located at the control level. It provides a lot of flexibility for the end-consumer thanks to platform-independent access to the PMS.

The PMS components selection was made based on a system installed in the footwear industry company and considering the applicability in other industries. Utilizing the existing base structure and already proven sensor systems from the previous PMS [2] allowed concentrating mainly on newly added components. The most notable is electrical current measuring hardware. It provides easy integration, low cost per node, and scalability. In a particular system, the current-based monitoring is employed for

most sewing machines- and facility electricity supply monitoring. The software components are selected explicitly to embed functions into the control level. However, it is impossible to avoid management-level PC entirely when using all the system functionalities. Therefore, a modular design principle containing optional software components is used. The overall system installation process included renewal of the electricity system at the company and installation of PMS. Electricity system modifications are not a natural part of the system's installation. However, it was needed considering the electricity system's noncompliance with the requirements and extra precautions taken during the pilot run. As a result, PMS acquiring 39 physical signals was achieved together with existing hardware. The installed PMS components cost is evaluated as around 8000 euros. Considering the system principle of being a one-time investment, cost efficiency is achieved in approximately five years.

The central weight of the system relies on software development, which is concentrated in control level PLC. The software development emphasized standardizing, using modular blocks, assembled into specific algorithms in different use-cases. The majority of them are present in production monitoring, where the most substantial are related to current-based monitoring, providing options such as standard deviation-based monitoring or automatic threshold calibration algorithms. The maintenance management algorithms help track equipment maintenance needs based on usage and conditions to add another value dimension to the system. The only functionality which was not fully achieved during the work was production prediction due to insufficient time and available data for development. Despite this, a strong basis was formed for future developments. The newly deployed visualization platform was built on similar principles using a uniform style of equipment presentation, popup templates, and relevant background to give an overview of the production. On top of the collected data, the visualization embeds all the essential configurations affecting the system's execution. The reporting was supplemented with updated reports for production monitoring and newly added reports for the environment and facility monitoring. Furthermore, the on-demand reporting feature was added, leveraging the web interface embedded into PMS visualization.

The result of this thesis is a complete PMS, developed from a product perspective and complying with the design requirements. The selected components of the system allow it to be versatile and scalable to be applicable in other industries. In order to test the system in natural conditions, it was installed in a footwear industry company, expanding an existing system. After a short test period, it can already be seen that the expanded monitoring area provides a better overview of activities and operations without requiring user intervention. In addition, obtaining information from the new system is much easier and more flexible. This, in turn, results in better process planning and monitoring in production enterprise. However, further development is needed to finalize the maintenance management views integration with the visualization platform. Additionally, it is necessary to collect sufficient data from new sources to continue with prediction functionality development. Furthermore, the system itself will be constantly monitored to identify errors in exceptional situations and improve the system.

KOKKUVÕTE

Käesoleva lõputöö eesmärk oli välja töötada spetsiaalselt väikese ja keskmise suurusega ettevõtetele mõeldud tootmise jälgimissüsteem (ingl *Production Monitoring System*, edaspidi PMS), mis aitab jälgida tootmise efektiivsust, seadmete kasutust ja personali panust. Kuigi viimastel aastatel on turule jõudnud palju selleks tarbeks mõeldud süsteeme, esineb neis endiselt puudusi, mis viitavad edasiarendamise vajadusele. Olemasolevate süsteemide analüüs näitas selgeid mustreid, kus peamised probleemid on kõrged haldamisnõuded, kallid teenusetüüpi lahendused ja mittetööstusliku riistvara kasutamisest tulenevad tehnilised aspektid. Seetõttu püstitati analüüsi tulemusena peamised eesmärgid süsteemi disainiks. Esitatud töö arendab edasi bakalaureusetöös [2] loodud süsteemi, mis tugineb tööstusautomaatika põhimõtetele. Seekord võeti aga kasutusele standardiseeritum ja süsteemsem lähenemine, et töötada välja süsteem kui toode, mis oleks rakendatav erinevates tööstusharudes. Lisaks laiendati süsteemi funktsioone, et pakkuda paremat ülevaadet ettevõtte tegevusest.

Süsteemile seatud eesmärkide põhjal teostati PMS-i kontseptsiooni projekteerimine, mis oli aluseks tehnilisele arendusele. Süsteemi nõuded on seatud toote vaatenurgast, arvestades ka testplatvormi ettevõtte vajadusi. Süsteemi funktsionaalsused võib jagada nelja omavahel seotud kategooriasse. Põhiline on tootmisseire koos erinevate funktsioonidega seirevajaduste katmiseks. Keskkonna- ja rajatise seire annab lisateavet tootmiskeskkonna ja rajatisega seotud parameetrite kohta. Hooldusjuhtimine on PMS-i loomulik osa, kuna seadmete kasutusega seotud teave on tootmisseirest juba saadud. Lisaks jälgimisfunktsioonidele sisaldab süsteemi kontseptsioon tootmistulemuste prognoosimise võimekust. Kõige olulisem struktuurimuudatus mõjutab tarkvara, kuna enamik uue süsteemi toiminguid on koondatud juhtimistasandi programmeeritavasse kontrollerisse (ingl *Programmable Logic Controller*, edaspidi PLC). Suurima panuse sellesse annab uus lähenemine visualiseerimisele, kasutades süsteemi juhtimistasandil asuvat serverit. Lahendus pakub lõpptarbijale paindlikku kasutust, kuna juurdepääs PMS-ile on platvormist sõltumatu.

PMS-i komponentide valik tehti jalatsitööstuse ettevõttes paigaldatud süsteemi alusel, võttes samas arvesse rakendatavust ka teistes tööstusharudes. Olemasoleva põhistruktuuri ja juba end tõestanud andurisüsteemide kasutamine eelmisest PMS-ist [2] võimaldas keskenduda peamiselt uutele komponentidele. Kõige tähelepanuväärsem neist on elektrivoolu mõõtmise riistvara, mis pakub lihtsat integreeritavust, madalat hinda sõlme kohta ja skaleeritavust. Konkreetses süsteemis kasutatakse voolupõhist jälgimist enamiku õmblusseadmete ja rajatise elektrivarustuse jälgimiseks. Tarkvarakomponendid on valitud spetsiaalselt nii, et oleks võimalik koondada funktsioonid süsteemi juhtimistasandile. Süsteemi kõiki funktsioone kasutades on aga võimatu täielikult vältida ettevõtte juhtimistaseme arvutit. Seetõttu kasutatakse modulaarset disaini, mis sisaldab valikulisi tarkvarakomponente. Üldine süsteemi paigaldusprotsess hõlmas ettevõtte elektrisüsteemi uuendamist ja PMS-i paigaldamist. Elektrisüsteemi uuendamine ei ole süsteemi paigaldamise loomulik osa. See oli aga vajalik, arvestades elektrisüsteemi nõuetele mittevastavust ja piloottöö ajal rakendatud täiendavaid ettevaatusabinõusid. Selle tulemusel valmis koos olemasoleva riistvaraga 39 füüsilist signaali koguv PMS. Paigaldatud PMS-i komponentide maksumuseks hinnatakse umbes 8000 eurot. Süsteemi ühekordse investeeringu põhimõtet arvestades saavutatakse kuluefektiivsus aga ligikaudu viie aastaga.

Süsteemi põhirõhk on tarkvaraarendusel, mis on koondatud süsteemi juhtimistasandi PLC-sse. Tarkvaraarenduses keskenduti standardiseerimisele, kasutades modulaarseid plokke, mis on erinevatel kasutusjuhtudel spetsiifilisteks algoritmideks kokku pandud. Suurim osa neist on mõeldud tootmise seireks, kus kõige olulisemad on seotud voolupõhise monitooringuga, pakkudes selliseid võimalusi nagu standardhälbepõhine monitooring või automaatsed lävendi kalibreerimise algoritmid. Hooldushaldusalgoritmid aitavad jälgida seadmete hooldusvajadusi kasutuse ja tingimuste alusel, et lisada süsteemile veel üks väärtusmõõde. Ainus funktsionaalsus, mida töö käigus täielikult ei saavutatud, oli tootmise prognoosimine, kuna arendustegevuseks ei olnud piisavalt aega ega kättesaadavaid andmeid. Sellest hoolimata loodi edasisteks arendusteks tugev alus. Uus visualiseerimisplatvorm ehitati sarnastel põhimõtetel, kasutades ühtset seadmete esitluse stiili, hüpikakende malle ja asjakohast tausta, et anda ülevaade tootmisest. Lisaks kogutud andmetele sisaldab visualiseerimine kõiki olulisemaid süsteemi täitmist mõjutavaid seadeid. Raporteerimist täiendati uuendatud tootmisseire aruannetega ning lisatud keskkonna- ja rajatise seire aruannetega. Juurde lisati ka vajaduspõhise raporteerimise funktsioon, mis kasutab PMS-i visualiseerimisse manustatud veebiliidest.

Selle lõputöö tulemus on terviklik PMS, mis on välja töötatud toote vaatenurgast ja mis vastab projekteerimisnõuetele. Süsteemi valitud komponendid võimaldavad sellel olla mitmekülgne ja skaleeritav, et seda saaks rakendada ka teistes tööstusharudes. Süsteemi katsetamiseks tegelikes tingimustes paigaldati see jalatsitööstuse ettevõttesse, laiendades olemasolevat süsteemi. Pärast lühikest testperioodi on juba näha, et laiendatud seireala annab parema ülevaate tegevustest ja toimingutest ilma kasutaja sekkumiseta. Lisaks on uuest süsteemist info hankimine palju lihtsam ja paindlikum. See omakorda toob kaasa parema protsesside planeerimise ja jälgimise tootmisettevõttes. Edasine arendus on vajalik, et lõpetada hooldushalduse funktsionaalsuse vaadete integreerimine visualiseerimisplatvormiga. Lisaks on vaja koguda piisavalt andmeid uutest allikatest, et jätkata ennustusfunktsioonide arendamist. Ka edaspidi jälgitakse süsteemi pidevalt, et seda täiustada ja erandolukordades vigu tuvastada.

LIST OF REFERENCES

[1] S. Vaidya, P. Ambad and S. Bhosle, "Industry 4.0 – A Glimpse," in *ICMMD2017*, Maharashtra India, 2017, pp. 233-238. doi: 10.1016/j.promfg.2018.02.034.

[2] F.-G. Pääro, "Industrial work time monitoring system," B.S. Thesis, Sch. Of Eng., Taltech Univ., Tallinn, Estonia, 2020.

[3] T. Eiskop, A. Snatkin, K. Karjust and E. Tungel, "Production monitoring system design and implementation," *P EST ACAD SCI*, vol. 67, no. 1, pp. 10-16, Dec. 2018. doi: 10.3176/proc.2017.4.02.

[4] A. Snatkin, T. Eiskop, K. Karjust and J. Majak, "Production monitoring system development and modification," *P EST ACAD SCI*, vol. 64, no. 4S, pp. 567-580, Mar. 2015. doi: 10.3176/proc.2015.4S.04.

[5] H. Prasetyo, Y. Sugiarto and C. N. Rosyidi, "Design of an automatic production monitoring system on job shop manufacturing," in *AIP Conf. Proc.*, 2018. doi: 10.1063/1.5024080.

[6] W. Y. Yee, "IoT-based Production Output Monitoring System for Plastic Packaging Manufacturing Process," in *IOP Conf. Ser.: Mater. Sci. Eng.*, Bangkok Thailand, 2020. doi: 10.1088/1757-899X/864/1/012087.

[7] L. Wang, Y. Zhang and Z. Chen, "Automated Production Line Monitoring Base on Wireless Mesh Sensor Network," *2020 39th Chinese Control Conference (CCC)*, 2020, pp. 6023-6027, doi: 10.23919/CCC50068.2020.9188808.

[8] O. Mörth, M. Eder, L. Holzegger and C. Ramsauer, "IoT-based monitoring of environmental conditions to improve the production performance," *Procedia Manuf.*, vol. 45, pp. 283-288, 2020. doi: 10.1016/j.promfg.2020.04.018.

[9] Evocon OÜ. "Product." Evocon. www.evocon.com/product/ (Accessed Sept. 27, 2021)

[10] OÜ GlobalReader. "Avaleht." GlobalReader. www.globalreader.eu/et/ (Accessed Sept. 25, 2021)

[11] D. Westrom and G. Immerman, "Reinventing the IoT Platform for Discrete Manufacturers," MachineMetrics, Northampton, MA, USA, [Online]. Available: www.machinemetrics.com/downloads#whitepapers (Accessed Oct. 19, 2021).

[12] Matics Manufacturing Analytics Ltd. "Solution." Matics. www.matics.live/solution/technology/#plug_play_agile_solution (Accessed Oct. 20, 2021)

[13] Monitor-Box Ltd. “M-Box.” Monitor-Box. www.monitor-box.com/m-box/ (Accessed Oct. 20, 2021)

[14] F. Wu, Z. Miao and C. He, "Remote Monitoring System for Intelligent Slaughter Production Line Based on Internet of Things and Cloud Platform," *2020 11th International Conference on Prognostics and System Health Management (PHM-2020 Jinan)*, 2020, pp. 538-542, doi: 10.1109/PHM-Jinan48558.2020.00104.

[15] A. Tarallo, G. D. Gironimo, R. Mozzillo and R. Amicis, “A cyber-physical system for production monitoring of manual manufacturing processes,” *IJIDeM*, vol. 14, no. 4, pp. 1235-1241, Nov, 2018, doi: 10.1007/S12008-018-0493-5.

[16] F. Yan, H. Zhou, Z. Peng, M. Chen, Y. Xiong and Z. Ren, "An Industrial Environmental Security Monitoring System in Mobile Device Based on Soft PLC," *2020 International Conference on Intelligent Transportation, Big Data & Smart City (ICITBS)*, 2020, pp. 711-715, doi: 10.1109/ICITBS49701.2020.00157.

[17] N. Sharma, “Evolution of IoT to IIoT: Applications & Challenges,” *ICICC*, May. 2020. doi: 10.2139/ssrn.3603739.

[18] A. Atutxa, D. Franco, J. Sasiain, J. Astorga, and E. Jacob, “Achieving Low Latency Communications in Smart Industrial Networks with Programmable Data Planes,” *Sensors*, vol. 21, no. 15, p. 5199, Jul. 2021. doi: 10.3390/s21155199.

[19] D. Raposo, A. Rodrigues, S. Sinche, J. Sá Silva, and F. Boavida, “Industrial IoT Monitoring: Technologies and Architecture Proposal,” Sensors, vol. 18, no. 10, p. 3568, Oct. 2018. doi: 10.3390/s18103568.

[20] X. Jiang, M. Lora, and S. Chattopadhyay, “ An Experimental Analysis of Security Vulnerabilities in Industrial IoT Devices,” ACM Trans. Internet Technol., vol. 20, no. 2, pp. 1-24, May. 2020. doi: 10.1145/3379542.

[21] S. Jaloudi, “Communication Protocols of an Industrial Internet of Things Environment: A Comparative Study,” Future Internet, vol. 11, no. 3, p. 66, Mar. 2019. doi: 10.3390/fi11030066.

[22] K. S. Shinde and P. H. Bhagat, "Industrial process monitoring using loT," *2017 I-SMAC*, pp. 38-42, Feb. 2017. doi: 10.1109/I-SMAC.2017.8058374.

[23] E. Irisarri, M. V. García, F. Pérez, E. Estévez and M. Marcos, "A model-based approach for process monitoring in oil production industry," *2016 IEEE 21st ETFA*, pp. 1-4, Sept. 2016. doi: 10.1109/ETFA.2016.7733633.

[24] F.-G. Pääro, "Computerized maintenance management system: case study and conceptual design," Course paper, Sch. Of Eng., Taltech Univ., Tallinn, Estonia, 2021.

[25] L. del C. Ng Corrales, M. P. Lambán, M. E. Hernandez Korner, and J. Royo, "Overall Equipment Effectiveness: Systematic Literature Review and Overview of Different Approaches," Applied Sciences, vol. 10, no. 18, p. 6469, Sep. 2020. Doi: 10.3390/app10186469.

[26] MachineMetrics, "Reinventing the Industrial IoT Platform for Manufacturing," MachineMetrics, Northampton, MA, USA, [Online]. Available: www.machinemetrics.com/downloads#brochures (Accessed Oct. 27, 2021).

[27] MachineMetrics, "MachineMetrics Service," MachineMetrics, Northampton, MA, USA, [Online]. Available: www.machinemetrics.com/downloads#brochures (Accessed Sept. 27, 2021).

[28] C. Krupitzer, V. Lesch, M. Züfle, S. Kounev, S. Müller, J. Edinger, C. Becker, D. Schäfer and A. Lemken, "A survey on Human Machine Interaction in Industry 4.0," ArXiv, vol. 1, no.1, Feb. 2020.

[29] J. Lee, H. Davari, J. Singh and V. Pandhare, "Industrial Artificial Intelligence for industry 4.0-based manufacturing systems," *Manuf. Lett.*, vol. 18, pp. 20-23, Oct. 2018. doi: 10.1016/J.MFGLET.2018.09.002.

[30] M. Bertolini, D. Mezzogori, M. Neroni and F. Zammori, "Machine Learning for industrial applications: A comprehensive literature review," *Expert Syst. Appl.*, vol. 175, p. 114820, Aug. 2021. doi: 10.1016/J.ESWA.2021.114820.

[31] D. F. Hesser and B. Markert, "Tool wear monitoring of a retrofitted CNC milling machine using artificial neural networks," *Manuf. Lett.,* vol. 19, pp. 1-4, Jan. 2019. doi: 10.1016/J.MFGLET.2018.11.001.

[32] M. Khanzadeh, S. Chowdhury, M. Marufuzzaman, M. A. Tschopp and L. Bian, " Porosity prediction: Supervised-learning of thermal history for direct laser deposition," *J Manuf Syst*, vol. 47, pp. 69-82, Apr. 2018. doi: 10.1016/J.JMSY.2018.04.001.

[33] P. Agarwal, M. Tamer, M. H. Sahraei and H. Budman, "Deep Learning for Classification of Profit-Based Operating Regions in Industrial Processes," *Ind. Eng. Chem. Res.*, vol. 59, no. 6, pp. 2378-2395, Feb. 2019. doi: 10.1021/ACS.IECR.9B04737.

[34] P.-H. Wang, G.-H. Lin and Y.-C. Wang, "Application of Neural Networks to Explore Manufacturing Sales Prediction," *Appl. Sci.*, vol. 9, no. 23, Nov. 2019. doi: 10.3390/app9235107.

[35] E. R. Abraham, J. G. Mendes dos Reis, O. Vendrametto, P. L. de Oliveira Costa Neto, R. Carlo Toloi, A. E. de Souza and M. de Oliveira Morais, "Time Series Prediction with Artificial Neural Networks: An Analysis Using Brazilian Soybean Production," *Agriculture*, vol. 10, no. 10, p. 475, Oct. 2020. doi: 10.3390/agriculture10100475.

[36] A. Khoshroo, A. Emrouznejad, A. Ghaffarizadeh, M. Kasraei and M. Omid, "Sensitivity analysis of energy inputs in crop production using artificial neural networks," *J. Clean. Prod.*, vol. 197, no. 1, pp. 992-998, Oct. 2018. doi: 10.1016/j.jclepro.2018.05.249.

[37] B. M. Negash and A. D. Yaw, "Artificial neural network based production forecasting for a hydrocarbon reservoir under water injection," *PETROL. EXPLOR. DEVELOP.*, vol. 47, no. 2, pp. 383-392, Apr. 2020. doi: 10.1016/S1876-3804(20)60055-6.

[38] G. Ciulla and M. Di Falco, "Artificial Neural Networks to Predict the Power Output of a PV Panel," *Int. J. Photoenergy*, vol. 2014, Jan. 2014. doi: 10.1155/2014/193083.

[39] Beckhoff Automation GmbH & Co. KG, "CX51x0 Embedded-PC Manual," version: 2.8, Feb. 2022.

[40] Beckhoff Automation GmbH & Co. KG, "SCT0xxx Coil current transformers," version: 1.2, Apr. 2021.

[41] Omron Corporation, "E2B Cylindrical proximity sensor," D116-E1-02, 2013.

[42] Optex Group, "Beam switch OS-12C / OS-12C (HT0.1)," 5911814, Jun. 2016.

[43] Vaisala, "GMW80 series carbon dioxide, humidity, and temperature transmitters for DCV," B211435EN-M, 2021.

[44] Evikon MCI OÜ, "RTD sensor with cable ET241," May 2021.

[45] Evikon MCI OÜ, "Temperature transmitter E2163," May 2021.

[46] Beckhoff Automation GmbH & Co. KG, "EL34xx 3-phase energy and power measurement terminals," version: 2.6, Mar. 2022.

[47] Beckhoff Automation GmbH & Co. KG. "EtherCAT Terminals." Beckhoff. https://www.beckhoff.com/et-ee/products/i-o/ethercat-terminals/ (Accessed Jan. 29, 2022)

[48] TwinCAT HMI. (version 1.12.754.4), Beckhoff Automation GmbH & Co. KG.

[49] Dream Report. (version 5.0 R20-3), Ocean Data System.

[50] Beckhoff Automation GmbH & Co. KG. "TFxxxx | TwinCAT 3 Functions." Beckhoff. https://www.beckhoff.com/et-ee/products/automation/twincat/tfxxxx-twincat-3-functions/ (Accessed Feb. 11, 2022)

[51] Vaisala, "User guide: Vaisala CARBOCAP Carbon dioxide, Humidity and Temperature Transmitters. GMW80 Series," M211748EN-H, 2021.

[52] E216x Configurator. (version 4.0), Evikon MCI.

[53] TKD Kabel, "ÖPVC-JZ/OZ-CY," Jan. 2006.

[54] Beckhoff Automation GmbH & Co. KG. "TF6250 | TwinCAT 3 Modbus TCP." Beckhoff. https://www.beckhoff.com/et-ee/products/automation/twincat/tfxxxx-twincat-3-functions/tf6xxx-tc3-connectivity/tf6250.html (Accessed Feb. 12, 2022)

[55] Beckhoff Automation GmbH & Co. KG. "TF6420 | TwinCAT 3 Database Server." Beckhoff. https://www.beckhoff.com/et-ee/products/automation/twincat/tfxxxx-twincat-3-functions/tf6xxx-tc3-connectivity/tf6420.html (Accessed Feb. 12, 2022)

[56] Beckhoff Automation GmbH & Co. KG, "Machine Learning- and Neural Network Inference Engine," version: 1.5, Mar. 2022.

[57] *Dream Report User documentation*, Ocean Data Systems, 2020.

APPENDICES

Appendix 1 – Requirements for the PMS

Table A1.1. General requirements for the system

General requirements	
Requirement	**Description**
Reliability	The system has to feature high reliability and low error probability.
Quality	The system has to offer high quality by using reliable hardware and best practices in software development.
Autonomous	The system must be as autonomous as possible, requiring the least amount of user interaction and operator inputs.
Scalability	The system has to be scalable to be applicable from tens to a few hundred of monitored equipment.
Unity	The system has to be as united as possible to lower the cost for initial acquisition and management afterward.
Customizability	The system has to offer possibilities for customization according to the company's specific needs.
Flexibility	Input acquiring methods have to be flexible to apply to varying equipment.
Direct	Output metrics and data from the system have to be as direct as possible to give a clear overview of the production.
Standardized	The system has to be as standardized as possible on behalf of hardware and software components to allow faster system assembly and management.

Table A1.2. Technical requirements for the system

Technical requirements	
Requirement	**Description**
Industrial grade hardware and software	Hardware and software components must comply with industrial standards to guarantee high system reliability and availability.
Highly compatible hardware and software	Hardware and software have to have good integrateability to develop a more coherent system.
Robust and reliable communication methods	Communication mediums and methods have to be reliable and withstand industrial conditions. All the communications have to use wire-based solutions.
Centralized architecture	The system architecture has to be as centralized as possible to minimize the footstep from the perspective of cost, management, and installation.
Expandable hardware and functionalities	Base components and system architecture have to allow expansion in terms of monitored equipment and functionalities.
Precise monitoring and sensor systems	The monitoring methods and algorithms have to guarantee precise monitoring of equipment. Used sensor systems have to provide reliable accuracy.
Intelligent monitoring algorithms and configuration possibilities	System control, monitoring, and configuration algorithms have to feature a good level of intelligence. Monitoring algorithms should allow flexible yet convenient ways to manage and configure them.

Table A1.2 continued.

Requirement	Description
Universal sensor systems	Sensor systems used for input acquiring should be selected considering universality and standardization. Applicability for varying equipment needs to be evaluated.
Easily observable visualization and data	System output data presentation to the user via visualization should be clear and easily observable.
Easily integratable to equipment	Sensor systems must be easily integratable into production equipment to allow faster and cheaper installation.
High availability and low error probability of the system	The system as a complete unit with its hardware and software components should guarantee high availability and low error probability

Table A1.3. Safety requirements for the system

Safety requirements	
Requirements	**Description**
Safe for humans	All system components have to be designed, installed, and operated in a safe manner for humans. The risk of electric shock should be eliminated by using proper installation methods and materials.
Safe for monitored equipment	Monitoring equipment should not harm existing production equipment mechanically or electrically.
Safe for the system itself	System design should guarantee its safety with proper protection devices and installation.
Electromagnetic compatibility	The system must be compatible with industrial EMC standards to be immune to interferences and not cause disturbances to other production equipment.

Table A1.4. Financial requirements for the system

Financial requirements	
Requirement	**Description**
One-time investment	The system has to be a one-time investment for the company. The system should not contain annually or monthly billed components and software.
Low maintenance and management costs	The system should be designed so that maintenance and management can be performed with low costs and effort.
Minimized amount of parts affected by wear and degradation over time	Components of the system have to be selected to withstand harsh conditions in the production environment. Components affected by wear and degradation over time should be avoided as much as possible.
Feasible system cost and received value ratio	System design and components selection should be made considering system cost and received value ratio. Input acquiring layer components should compensate the price of the base structure (central control hardware). Therefore, each additional monitored unit of equipment should lower the system price.

Appendix 2 – PMS Hardware technical specification

Table A2.1. Technical parameters of the Beckhoff CX5140 PLC [39]

Parameter	**Value/Description**
Model specification	CX5140-0175
Processor	Intel Atom E3845, 1.91 GHz, 4 cores
Main memory	4 GB DDR3 RAM
Persistent memory	Integrated 1-second UPS (1 MB on CFast card)
Interfaces	2 x RJ45, 1 x DVI-I, 4 x USB 2.0
Clock	Internal battery-backed clock (battery exchangeable)
Operating system	Windows 10 IoT Enterprise 2019 LTSC 64 bit, TwinCAT 3 runtime
Power supply	24 V DC (-15 %/+20 %)
Max. power consumption	16 W (23 W with loading UPS)
I/O connection	E-bus (EtherCAT-bus) with automatic recognition
Current supply I/O bus	2 A
Protection rating	IP20
Vibration/shock resistance	Conforms to EN 60068-2-6/EN 60068-2-27
EMC immunity/emission	Conforms to EN 61000-6-2/EN 61000-6-4

Table A2.2. Technical parameters of monitoring sensor systems

Parameter	**Value/Description**
Beckhoff SCT0121-0005 [40]	
Description	Coil-type current transformer
Application	Production equipment monitoring
Number of measured phases	1
Ratio	5/1 A
Accuracy class	0,5
Beckhoff SCT3111-0050 [40]	
Description	Ring-type current transformer
Application	Facility electricity monitoring
Number of measured phases	3
Ratio	3 x 50/1 A
Accuracy class	1
Omron E2B-M12KS04-M1-B1 [41]	
Description	M12 inductive sensor
Application	Production equipment monitoring via detecting moving metal object
Sensing distance	4 mm ± 10 %

Table A2.2 continued.

Parameter	Value/Description
Setting distance	0-3,2 mm
Detectable object	Ferrous metal
Power supply	10-30 V DC
Current consumption	10 mA max.
Output type	PNP open collector
Output load current	200 mA max.
Operation mode	NO
Optex OS-12C [42]	
Description	Active infrared sensor
Application	Products counting
Sensing distance	Configurable, 0-2 m, 2-5 m, 5-10 m
Detection method	Point to point near infrared light beam
Power supply	12-24 V AC, 12-30 VDC
Current consumption	135 mA max.
Output contact	Relay (50 V)
Output load current	300 mA
Operation mode	NO, NC
Response time	0,1 s
Vaisala GMW83RP [43]	
Description	Carbon dioxide, humidity, and temperature transmitter
Application	Indoor environment monitoring
Power supply	18-35 V DC, 24 V AC
Outputs	3 x 0-10 V DC
Temperature range	0…+50 °C
Temperature accuracy	±0,5 °C at +10…+30 °C
Humidity range	0…95 %RH
Humidity accuracy	±3 % at 0…80 % RH and +10…+30 °C
CO2 range	0…2000 ppm
CO2 accuracy	±(30 ppm + 3 % of reading) at +20…+30 °C
Evikon ET241 RTD with E2163 transmitter [44-45]	
Application	Outdoor temperature measurement
RTD type	PT100 (3-wire)
Power supply	12-36 V DC, nominal 24 V DC through 4-20 mA current loop
Transmitter output	4-20 mA
Temperature range	Configured, -50…+50°C
Transmitter accuracy	±0,25 %FSO for RTD

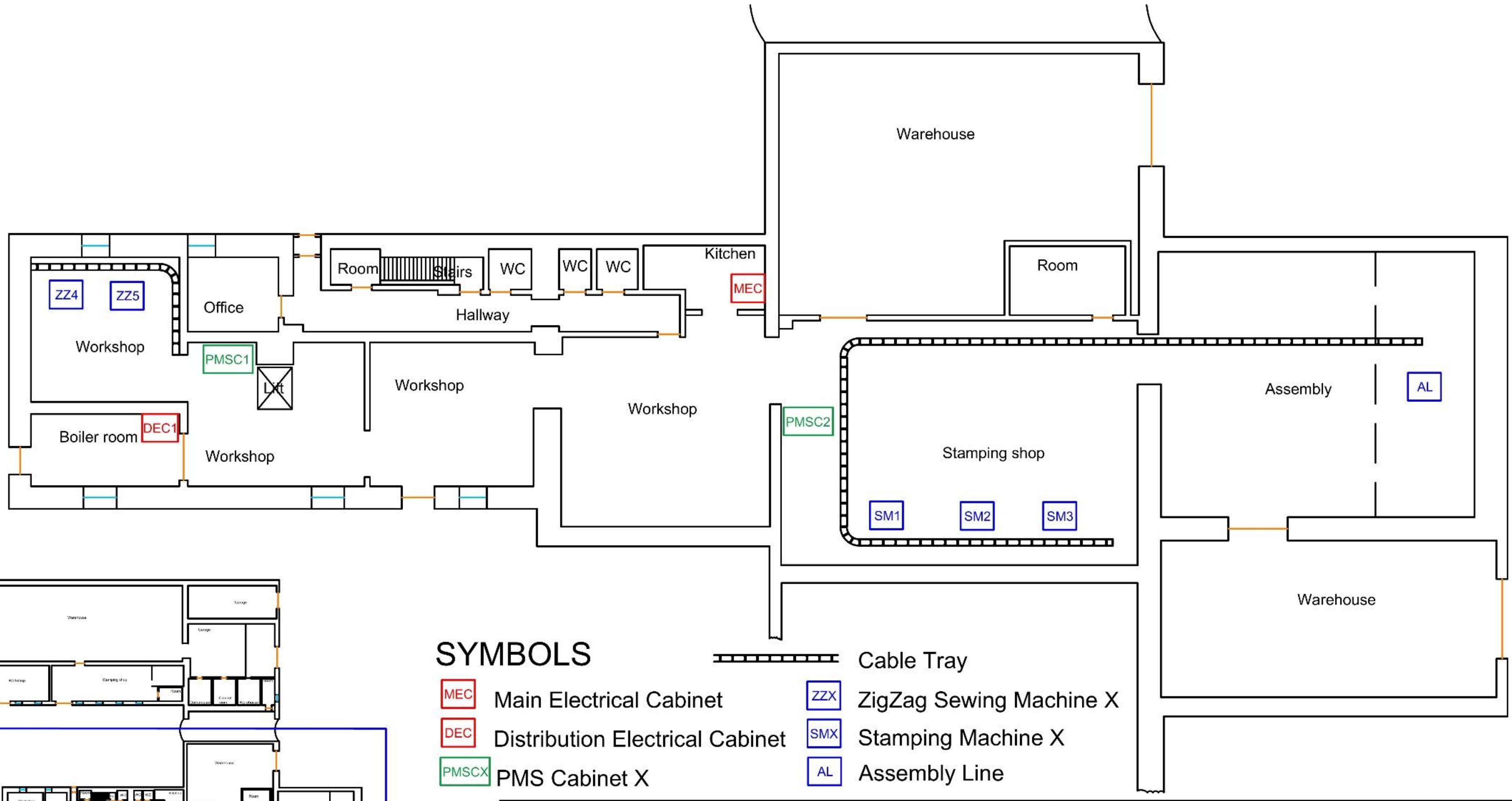
Table A2.3. Technical parameters of Beckhoff I/O terminals [47]

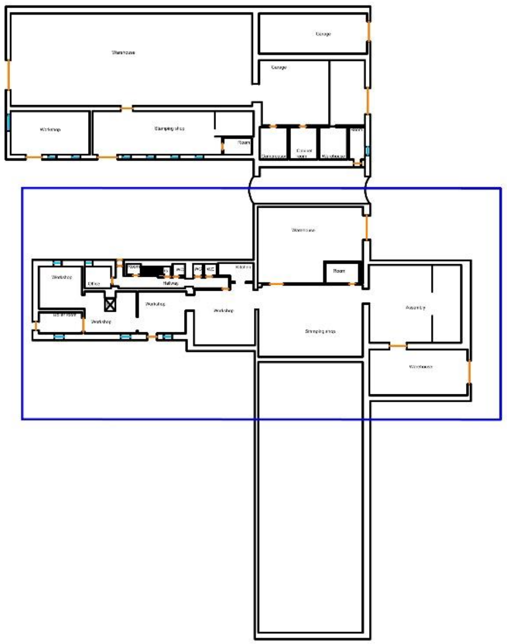
Parameter	Value/Description
EL3446	
Description	Current measurement terminal
Application	Production equipment monitoring via current consumption
Number of inputs	6 x current
Measuring current	Max. 1 A (AC/DC), via measuring transformers x A/1 A
Measuring error	0,3 % relative to full scale value
Update interval	20 ms at 50 Hz
EL3443	
Description	Power measurement terminal
Application	Facility electricity monitoring
Number of inputs	3 x current, 3 x voltage
Measuring current	Max. 1 A (AC/DC), via measuring transformers x A/1 A
Measuring voltage	Max. 480 V AC 3~ (UL_x-N: max. 277 V AC/240 V DC)
Measuring error	0,3 % relative to full scale value
Update interval	20 ms at 50 Hz
EL1008	
Description	Digital input terminal
Application	Production equipment monitoring via relays, inductive sensors and active infrared sensors
Number of inputs	8
Nominal voltage	24 V DC
Connection technology	1-wire
Input filter	3,0 ms
EL1809	
Description	Digital input terminal
Application	Production equipment monitoring via relays, inductive sensors and active infrared sensors
Number of inputs	16
Nominal voltage	24 V DC
Connection technology	1-wire
Input filter	3,0 ms
EL1262	
Description	Digital input terminal with oversampling
Application	Production equipment monitoring via inductive sensor applied for detecting a protruding object on a fast rotating shaft
Number of inputs	2
Nominal voltage	24 V DC
Connection technology	4-wire

Table A2.3 continued.

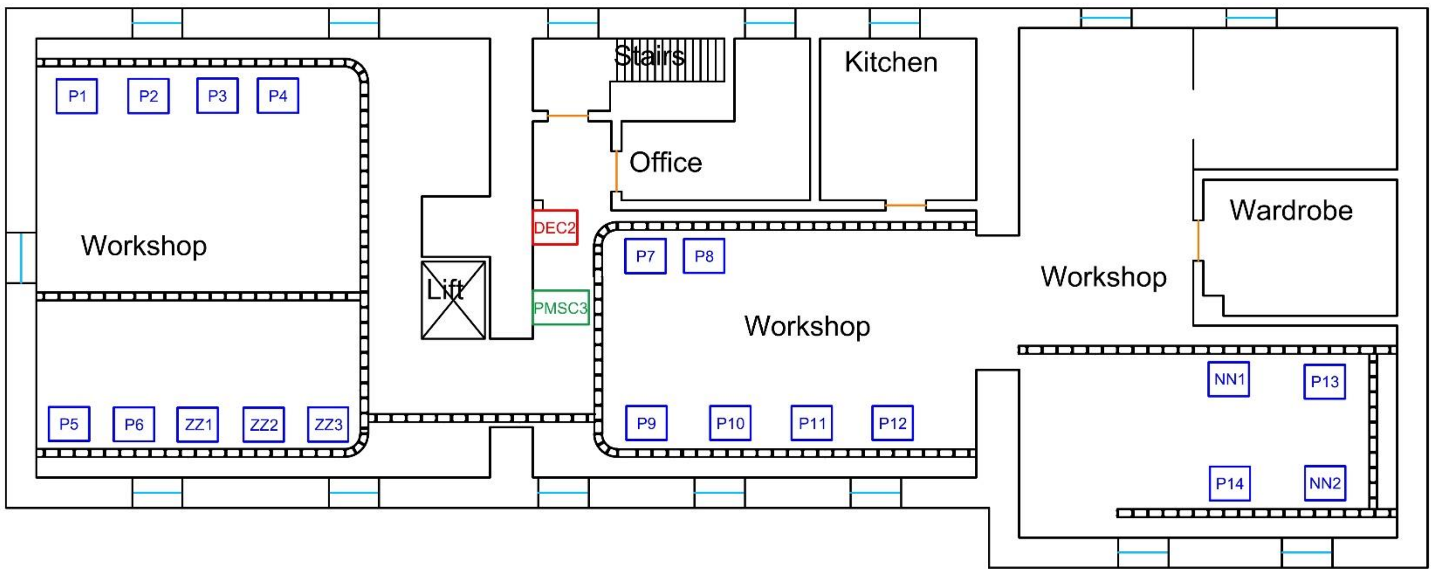
Parameter	Value/Description
Input filter	< 1 μs
EL3064	
Description	Analog input terminal
Application	Indoor environment monitoring
Number of inputs	4
Signal voltage	0…10 V
Resolution	12 bit (16 bit presentation including sign)
Measuring error	< ±0,3 % (relative to full scale value)
Connection technology	Single-ended
EL3022	
Description	Analog input terminal
Application	Outdoor temperature measurement
Number of inputs	2
Signal current	4…20 mA
Resolution	12 bit (16 bit presentation including sign)
Measuring error	< ±0,3 % (relative to full scale value)
Connection technology	Differential input

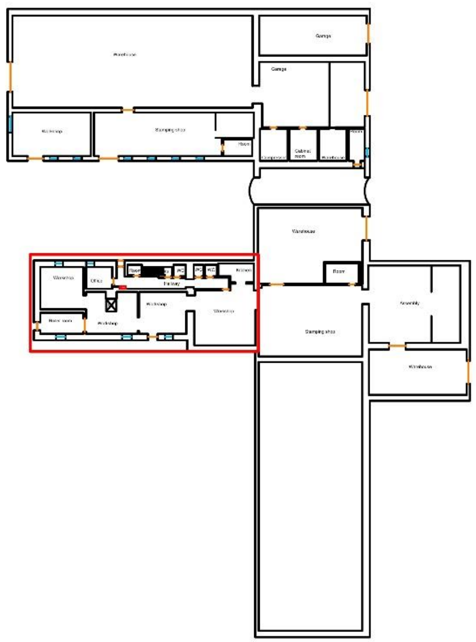
Appendix 3 – Location of production equipment and PMS hardware





TALTECH SCHOOL OF ENGINEERING	Master's thesis	Page / Pages: 1 / 2
Drawn: Fred-Georg Pääro		Production equipment and PMS hardware layout 1. floor
Supervisor: Kristjan Pütsep	Co-supervisor: Eduard Petlenkov	
Department of Electrical Power Engineering and Mechatronics	Production monitoring system	



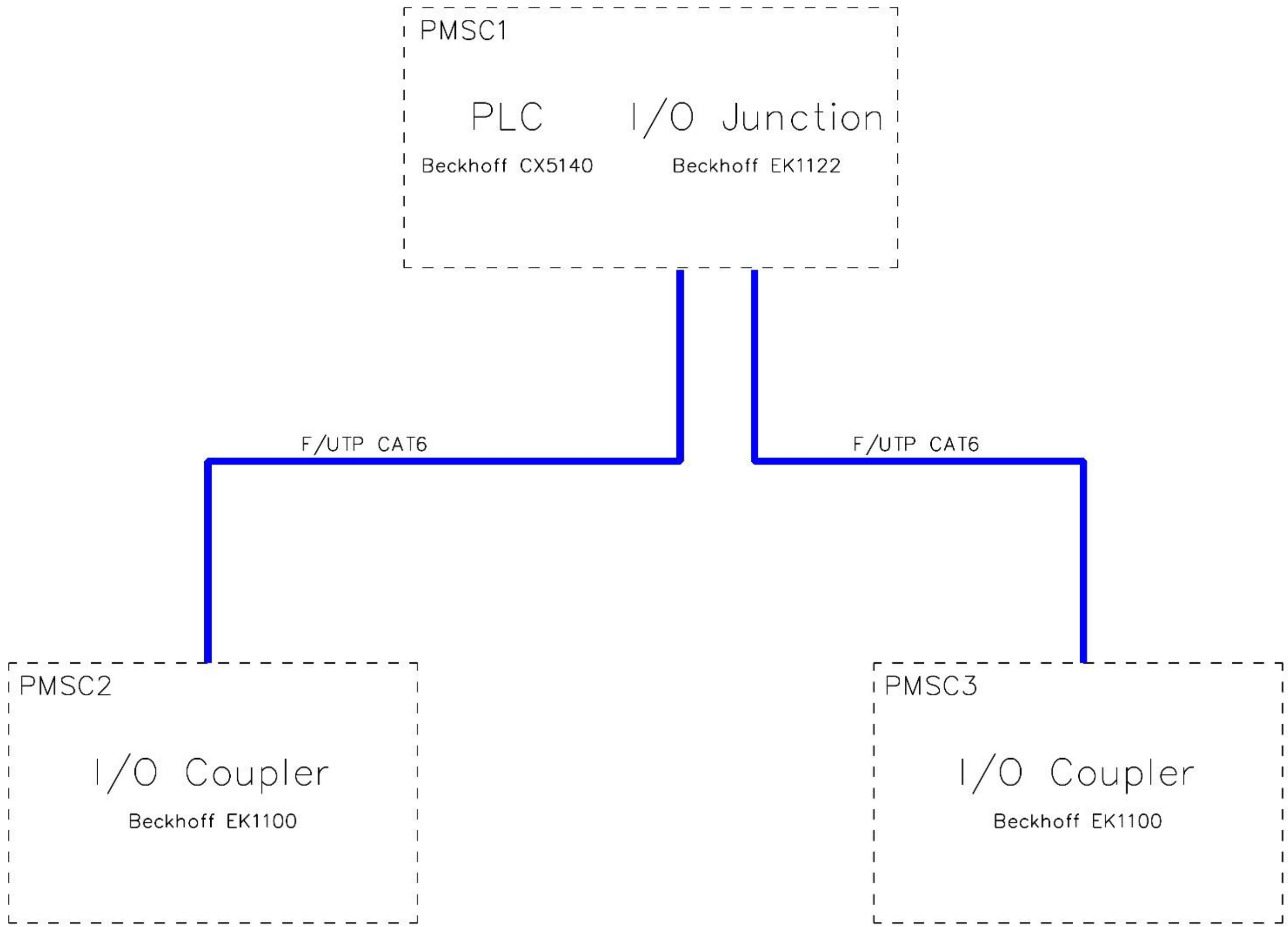


SYMBOLS

- DEC — Distribution Electrical Cabinet
- PMSCX — PMS Cabinet X
- Cable Tray
- PX — Post-bed Sewing Machine X
- ZZX — ZigZag Sewing Machine X
- NNX — Twin Needle Post-bed Sewing Machine X

TALTECH SCHOOL OF ENGINEERING	Master's thesis	Page / Pages: 2 / 2
Drawn: Fred-Georg Pääro		Production equipment and PMS hardware layout 2. floor
Supervisor: Kristjan Pütsep	Co-supervisor: Eduard Petlenkov	
Department of Electrical Power Engineering and Mechatronics		Production monitoring system

Appendix 4 – PMS circuitry schematics



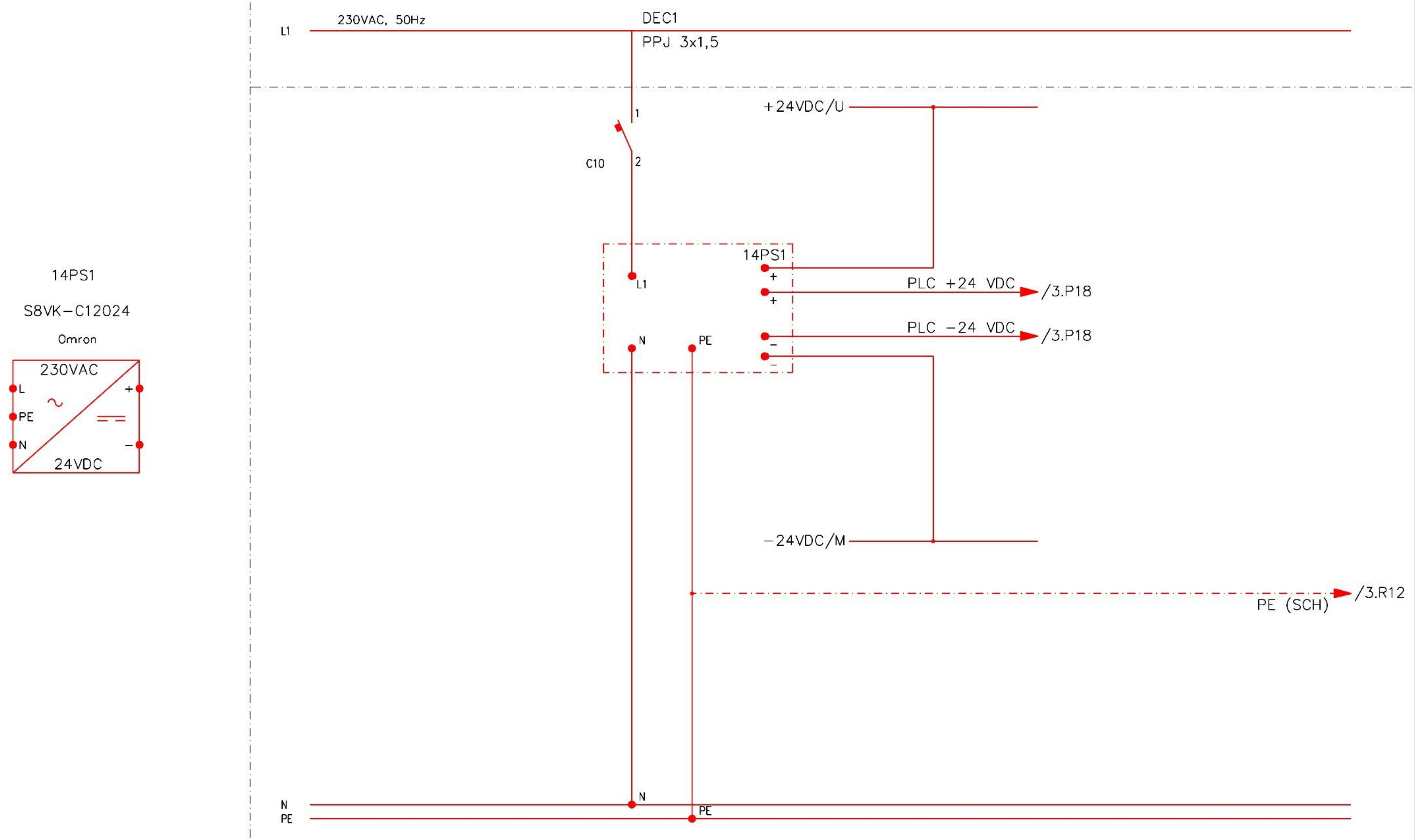
PMSC1 – Production Monistoring System Cabinet 1

PMSC2 – Production Monistoring System Cabinet 2

PMSC3 – Production Monistoring System Cabinet 3

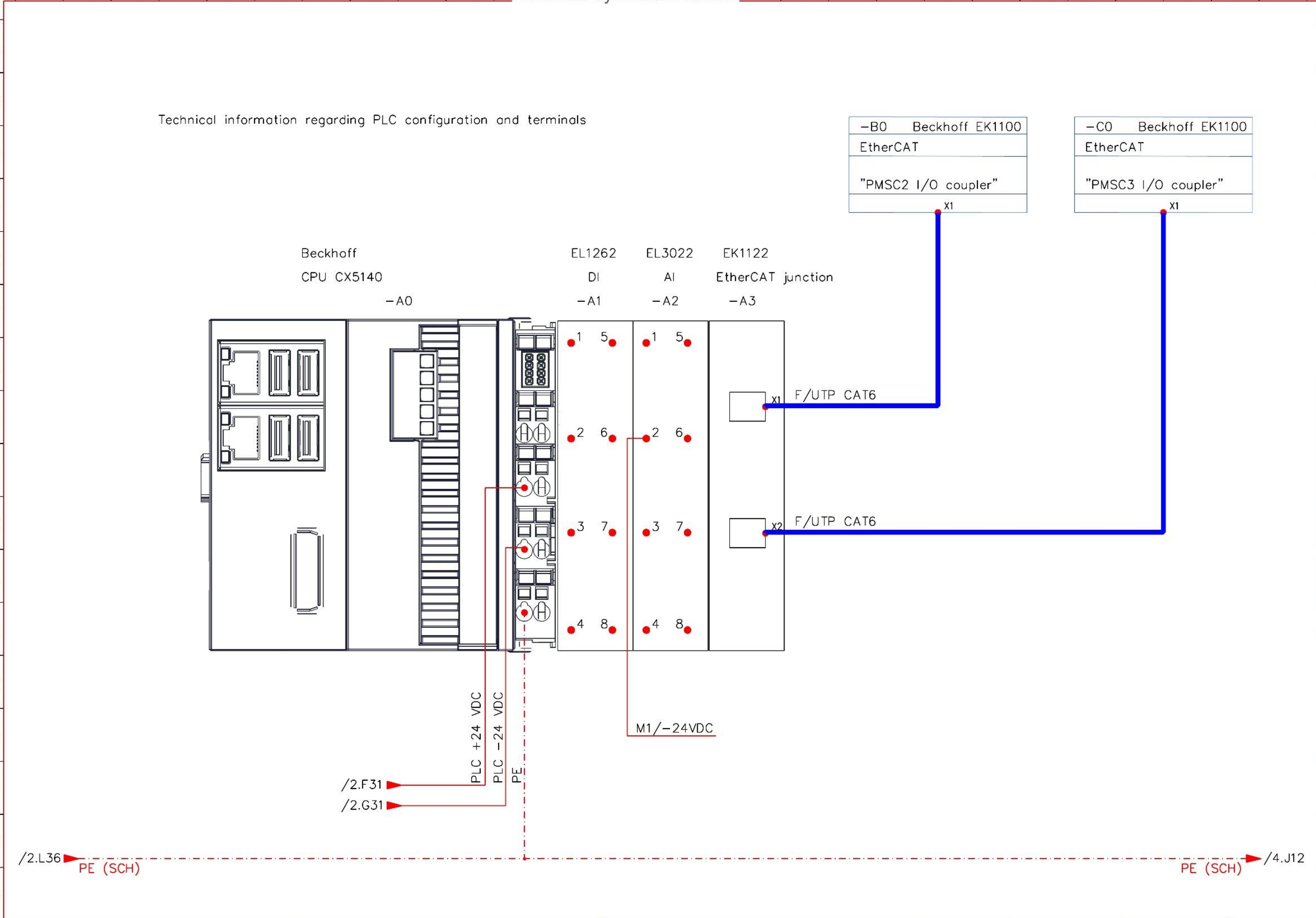
Production monitoring system Automation and communication structural schematic	Plan. /09.04.2022	Object ID	Electrical position	Job no. 1
	Draw. Fred-Georg Pääro	Sheet 1/15	Drawing no.	Schematic 1
	Check Kristjan Pütsep			

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :



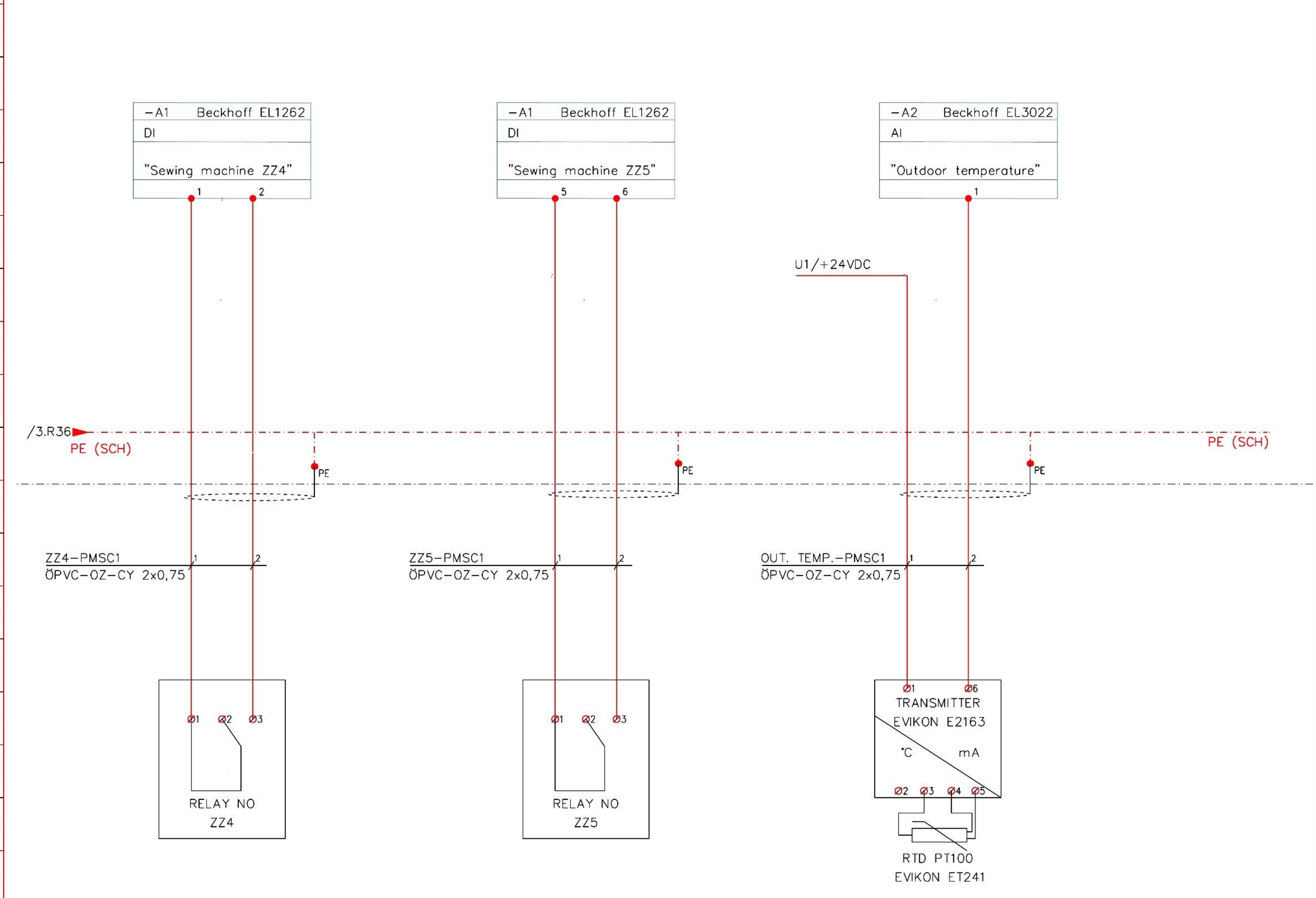
Production monitoring system PMSC1 cabinet supply 230VAC/24VDC power supply	Plan. /09.04.2022	Object ID	Electrical position +PMSC1	Job no. 1
	Draw. Fred-Georg Pääro	Sheet 2/15	Drawing no.	
	Check Kristjon Pütsep		Schematic 2	

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :



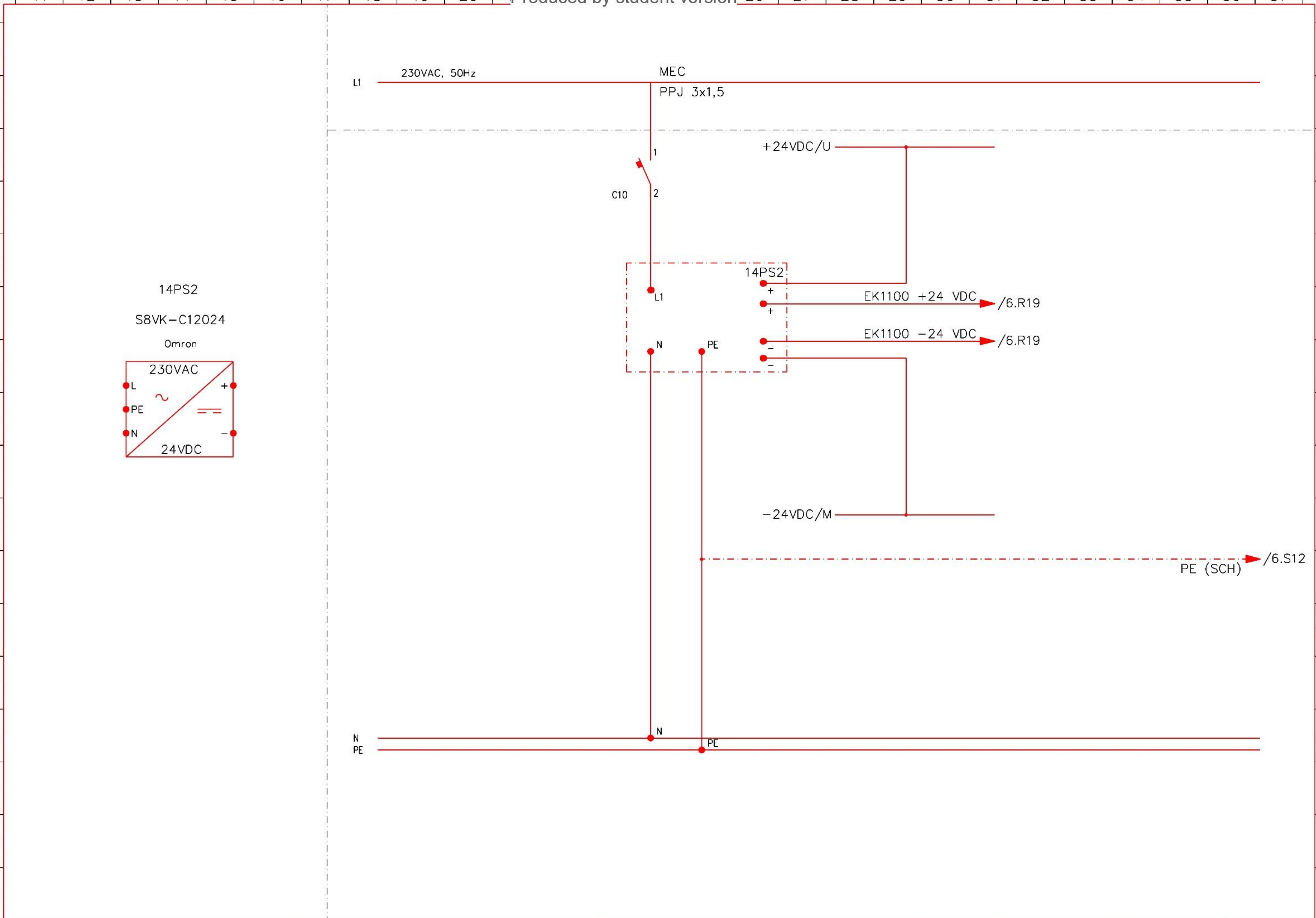
Production monitoring system PLC configuration Beckhoff CPU CX5140	Plan. /09.04.2022	Object ID	Electrical position +PMSC1	Job no. 1
	Draw. Fred-Georg Pääro	Sheet 3/15	Drawing no.	
	Check Kristjan Pütsep		Schematic 3	

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :



Production monitoring system PMSC1 sensor systems	Plan. /09.04.2022	Object ID	Electrical position +PMSC1
	Draw. Fred-Georg Pääro	Sheet 4 / 15	Job no. 1
	Check Kristjan Pütsep		Drawing no. Schematic 4

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :



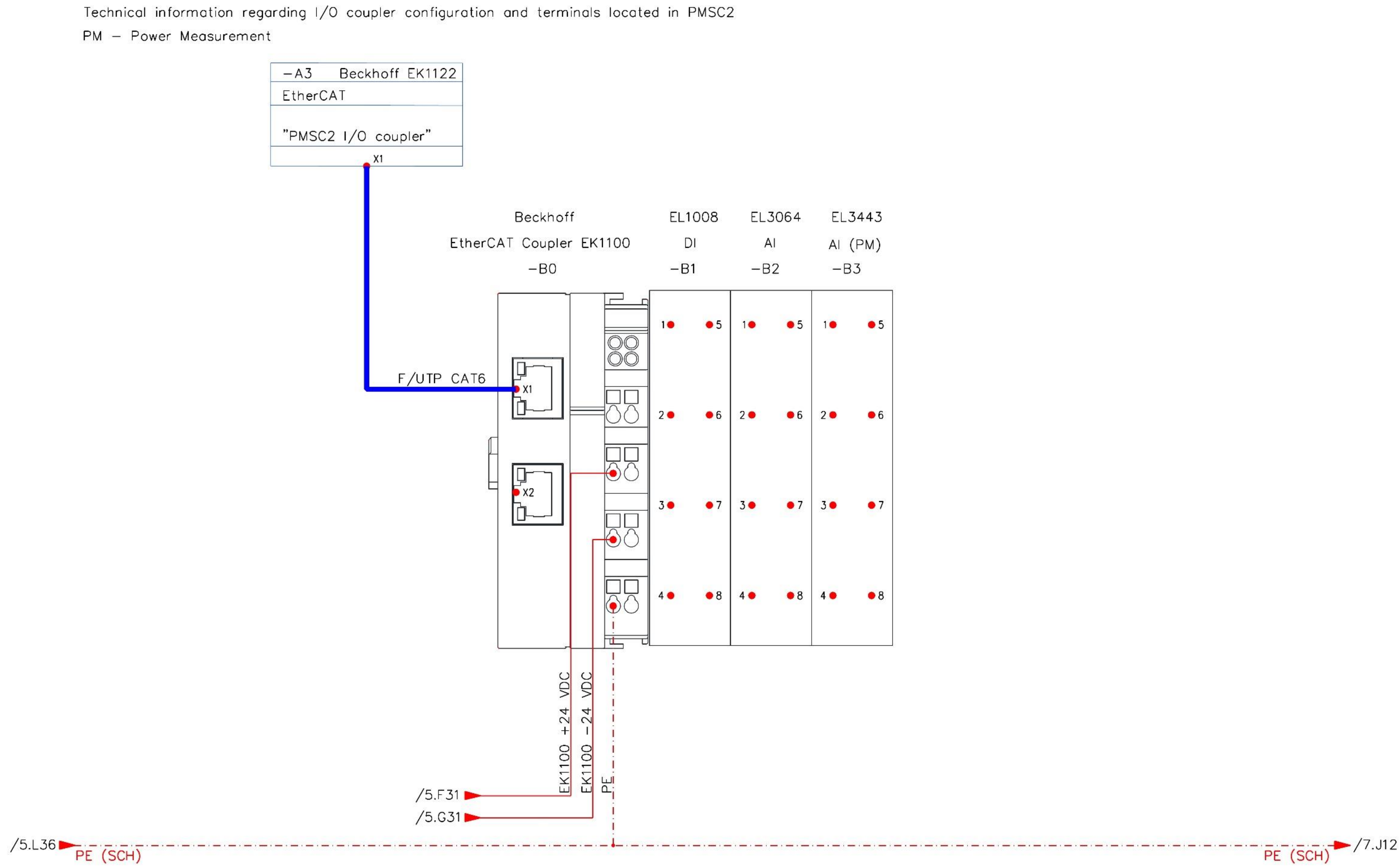
Plan. /09.04.2022	Object ID		Electrical position +PMSC2	Job no. 1
Draw. Fred-Georg Pääro	Sheet 5/15	Drawing no.		
Check Kristjan Pütsep				

Production monitoring system
PMSC2 cabinet supply
230VAC/24VDC power supply

Schematic 5

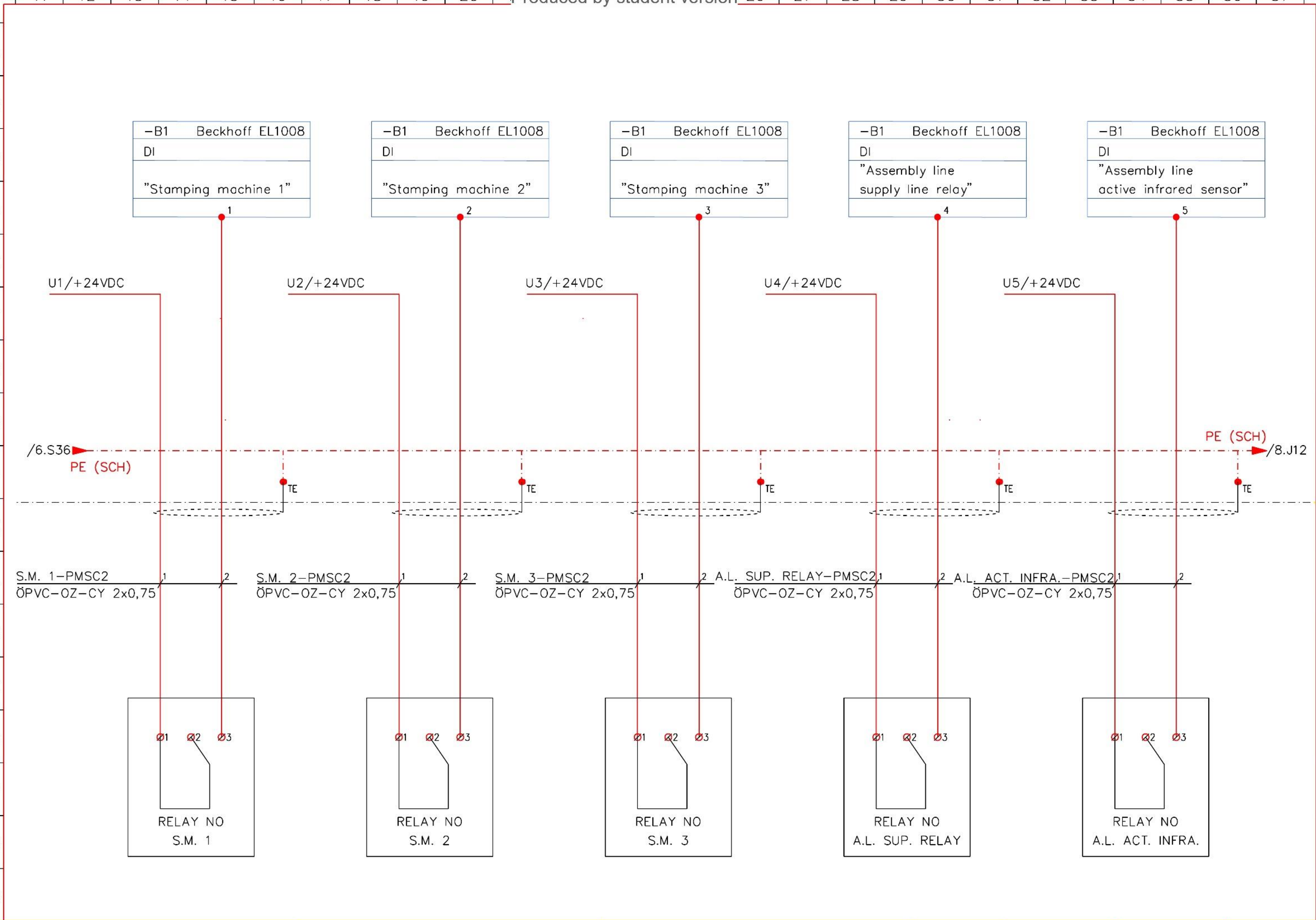
A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :

17.5.2022
5_Supply_PMSC2



Production monitoring system PMSC2 I/O coupler config. Beckhoff EK1100	Plan. /09.04.2022	Object ID	Electrical position +PMSC2	Job no. 1
	Draw. Fred-Georg Pääro	Sheet 6 / 15	Drawing no. Schematic 6	
	Check Kristjan Pütsep			

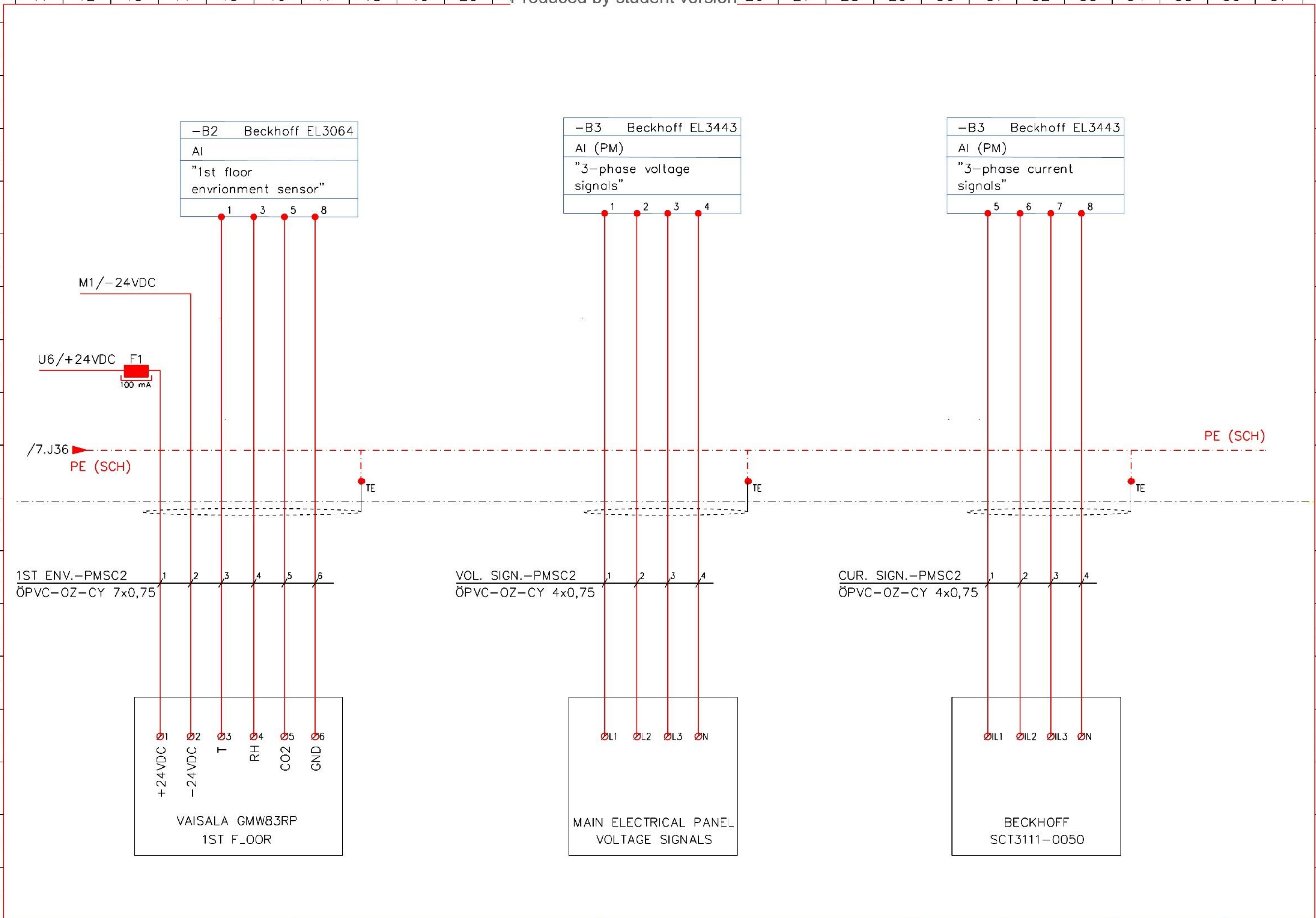
A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :



A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :

Production monitoring system
PMSC2 sensor systems

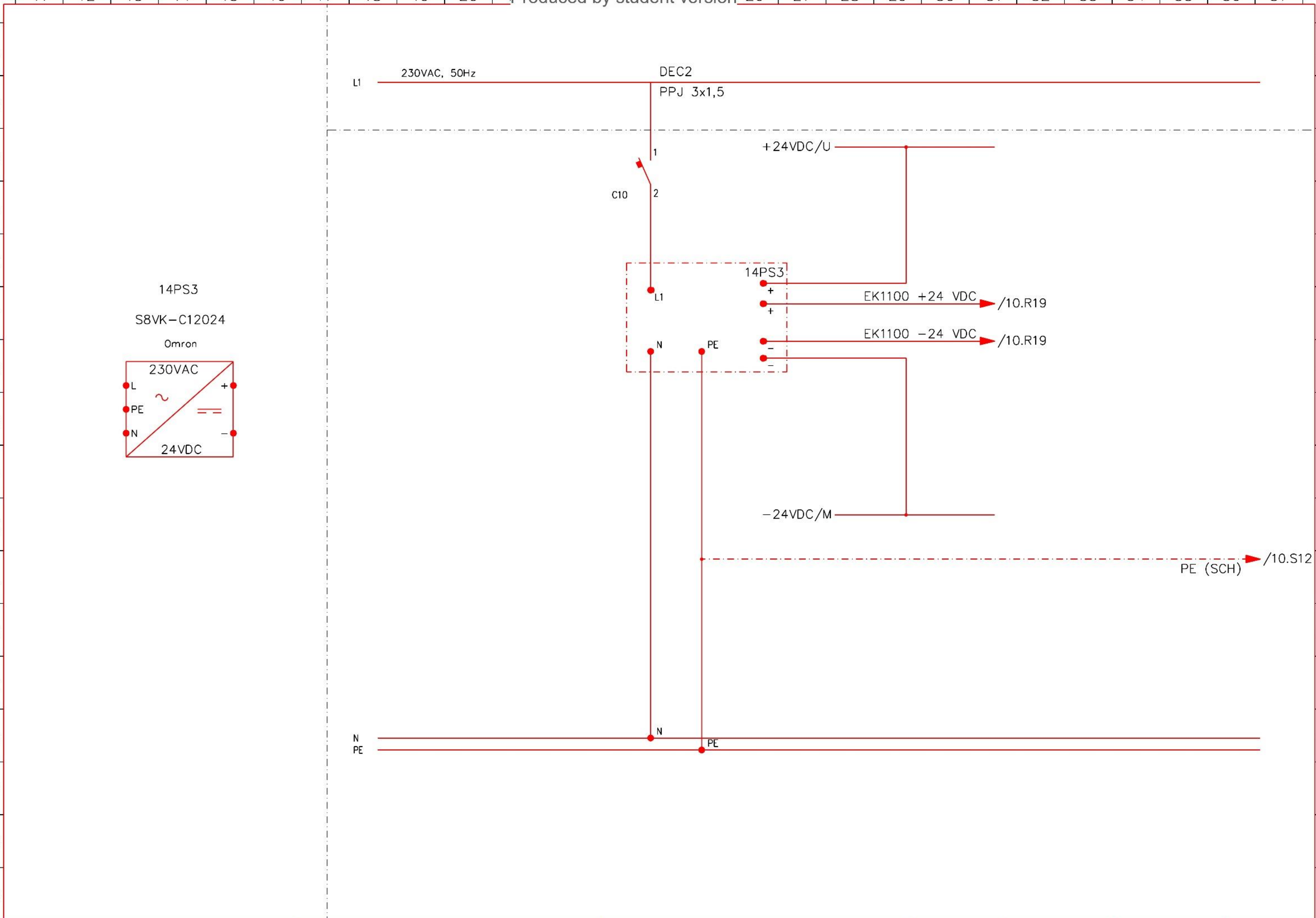
Plan. /09.04.2022	Object ID	Electrical position +PMSC2	Job no. 1
Draw. Fred-Georg Pääro	Sheet 7 / 15	Drawing no.	
Check Kristjan Pütsep		Schematic 7	



A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :

Production monitoring system
PMSC2 sensor systems

Plan. /09.04.2022	Object ID	Electrical position +PMSC2	Job no. 1
Draw. Fred-Georg Pääro	Sheet 8 / 15	Drawing no.	
Check Kristjon Pütsep		Schematic 8	



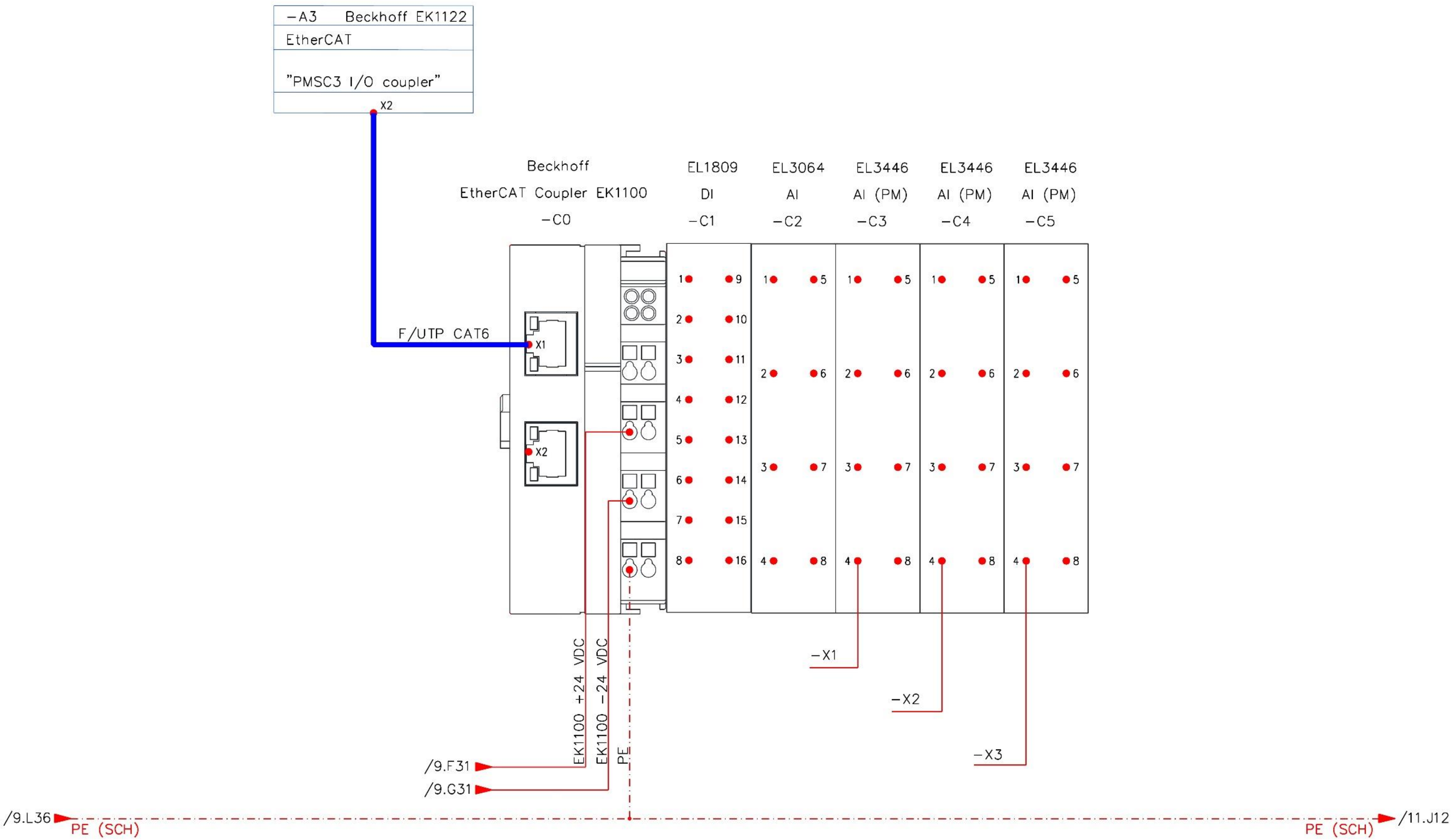
Production monitoring system
PMSC3 cabinet supply
230VAC/24VDC power supply

Plan. /09.04.2022	Object ID		Electrical position +PMSC3	Job no. 1
Draw. Fred-Georg Pääro	Sheet 9/15	Drawing no.		
Check Kristjan Pütsep		Schematic 9		

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :

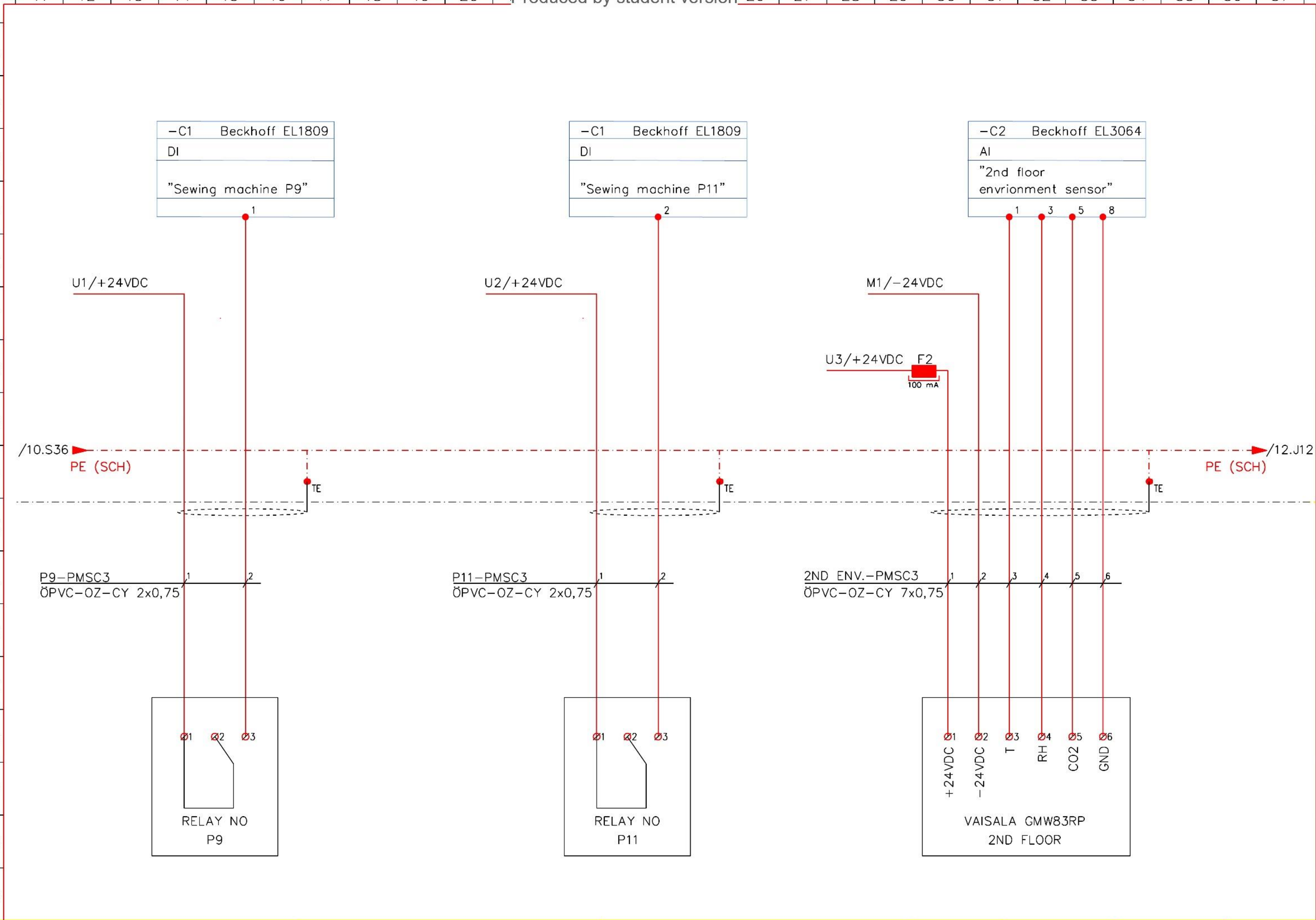
Technical information regarding I/O coupler configuration and terminals located in PMSC3

PM – Power Measurement



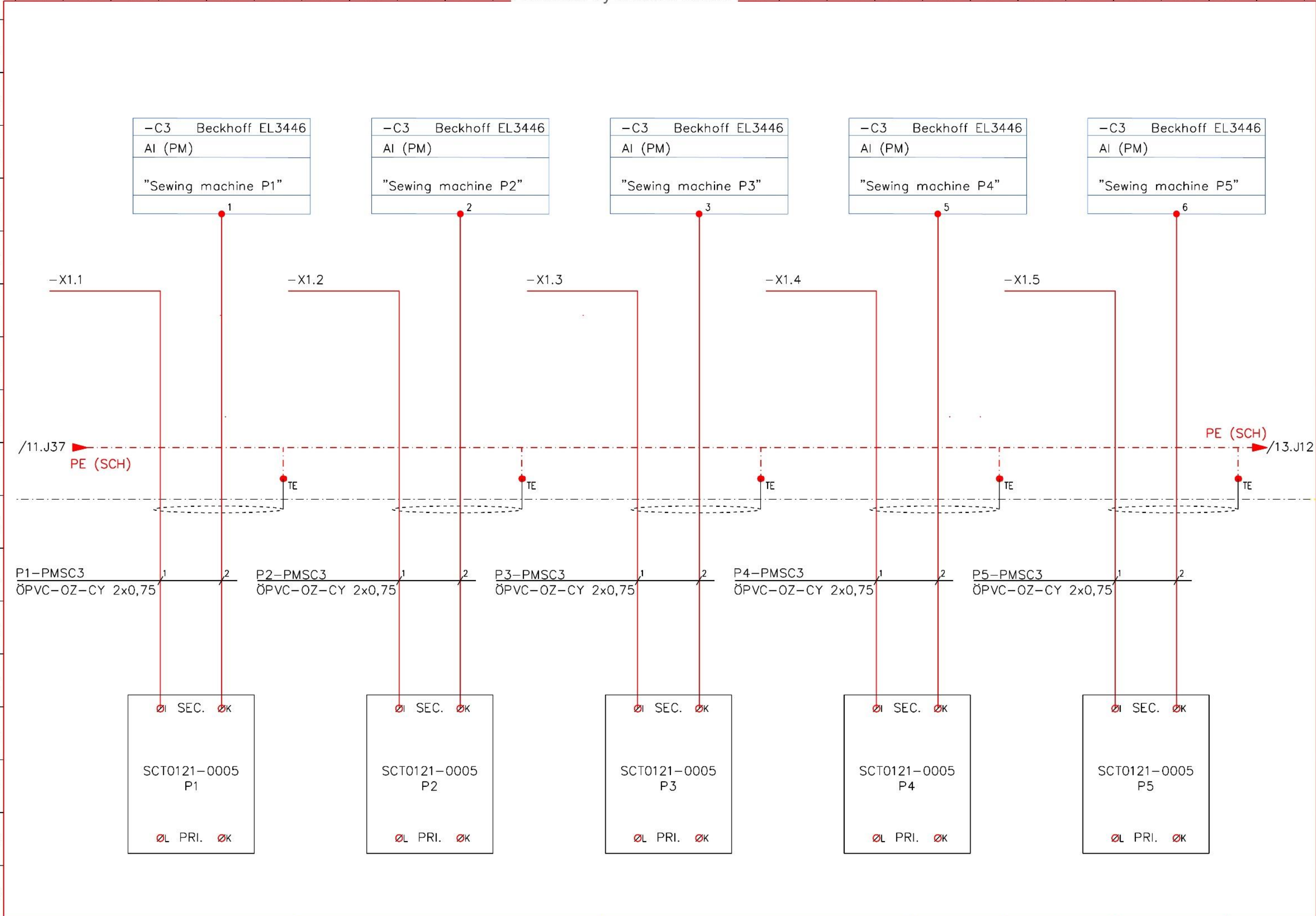
Production monitoring system PMSC3 I/O coupler config. Beckhoff EK1100	
Plan. /09.04.2022	Object ID
Draw. Fred-Georg Pääro	Sheet 10 / 15
Check Kristjan Pütsep	
Electrical position +PMSC3	Job no. 1
Drawing no.	Schematic 10

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :



Production monitoring system PMSC3 sensor systems	Plan. /09.04.2022	Object ID	Electrical position +PMSC3
	Draw. Fred-Georg Pääro	Sheet 11/15	Job no. 1
	Check Kristjan Pütsep	Drawing no.	Schematic 11

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :

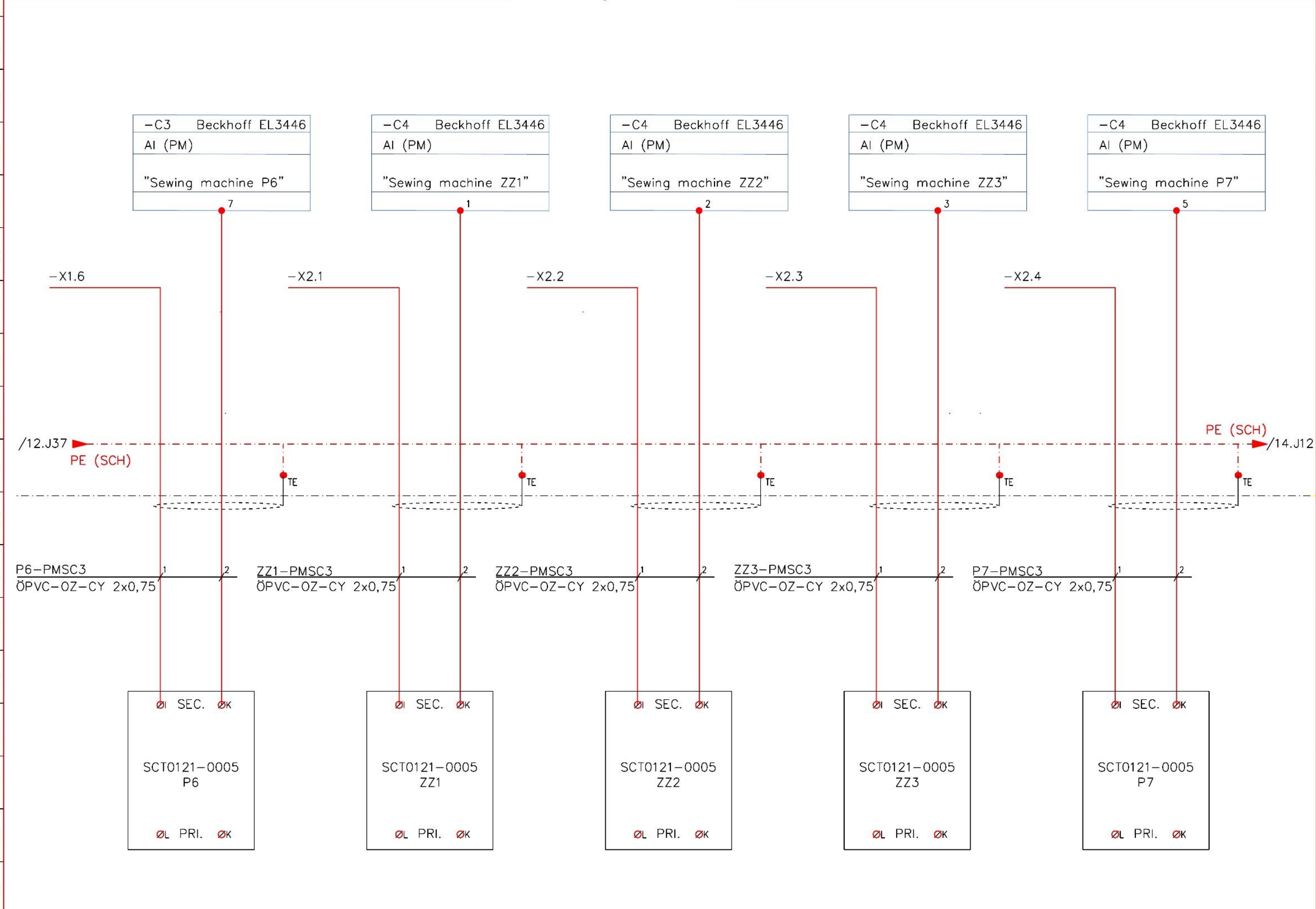


Plan. /09.04.2022	Object ID	Electrical position +PMSC3	Job no. 1
Draw. Fred-Georg Pääro	Sheet 12 / 15	Drawing no.	
Check Kristjan Pütsep			

Production monitoring system
PMSC3 sensor systems

Schematic 12

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :

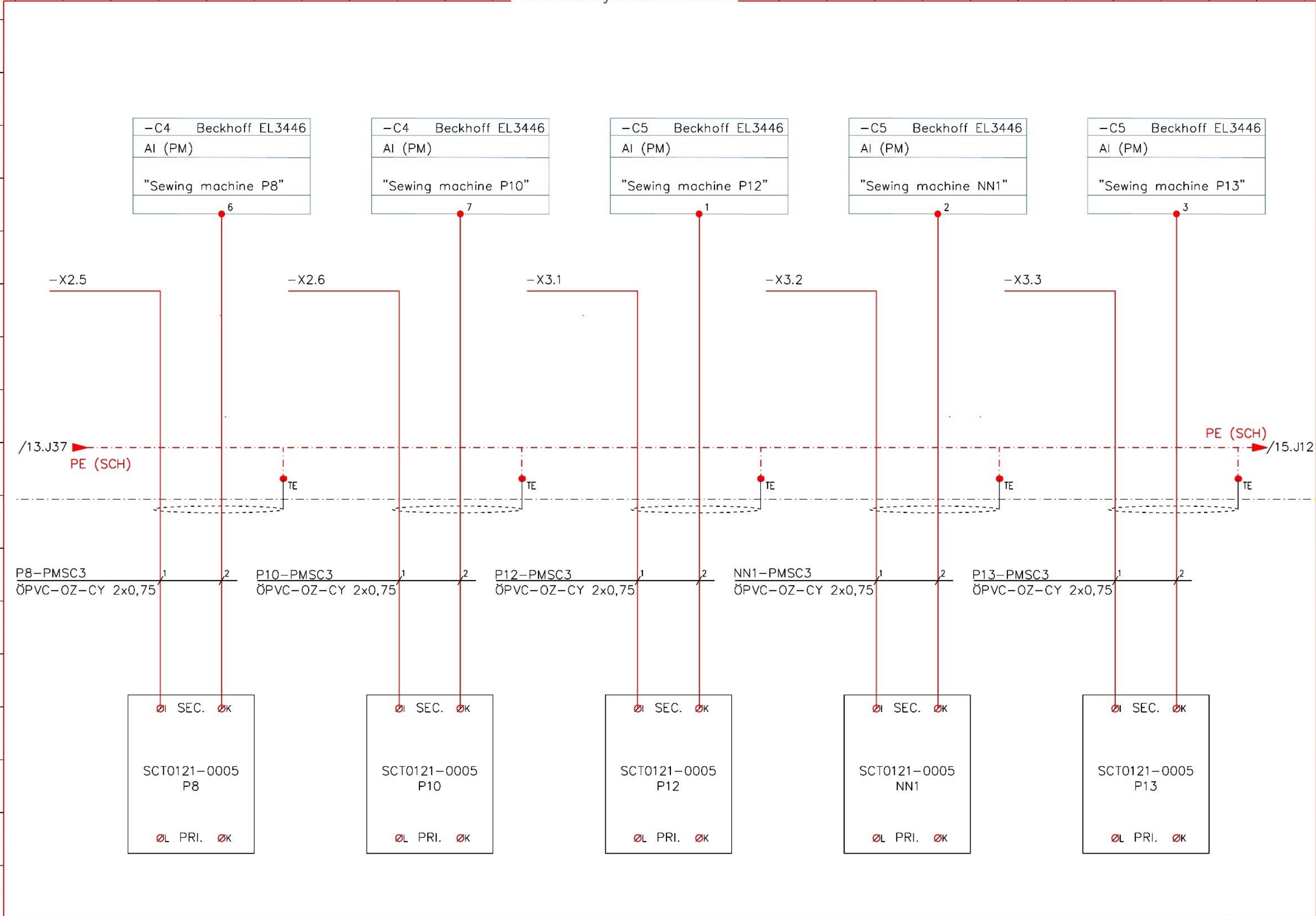


D Rev. :
E Rev. :
F Rev. :
A Rev. :
B Rev. :
C Rev. :

Production monitoring system
PMSC3 sensor systems

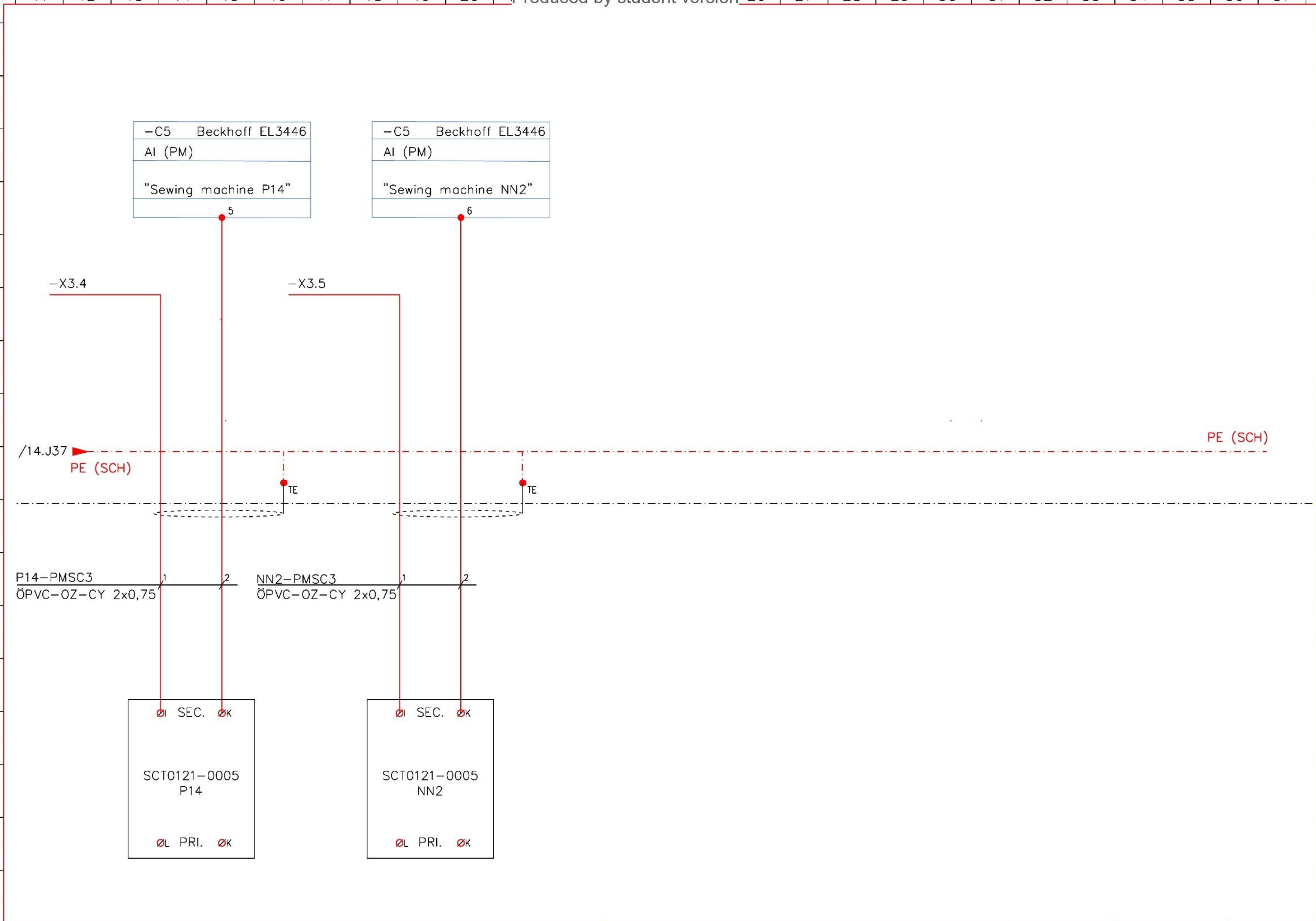
Plan. /09.04.2022	Object ID		Electrical position +PMSC3	Job no. 1
Draw. Fred-Georg Pääro	Sheet 13/15	Drawing no.		
Check Kristjan Pütsep				

Schematic 13



Production monitoring system PMSC3 sensor systems	Plan. /09.04.2022	Object ID	Electrical position +PMSC3	Job no. 1
	Draw. Fred-Georg Pääro	Sheet 14 / 15	Drawing no.	
	Check Kristjan Pütsep		Schematic 14	

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :



Production monitoring system PMSC3 sensor systems	Plan. /09.04.2022	Object ID	Electrical position +PMSC3	Job no. 1
	Draw. Fred-Georg Pääro	Sheet 15 / 15	Drawing no.	
	Check Kristjon Pütsep		Schematic 15	

A Rev. :
B Rev. :
C Rev. :
D Rev. :
E Rev. :
F Rev. :

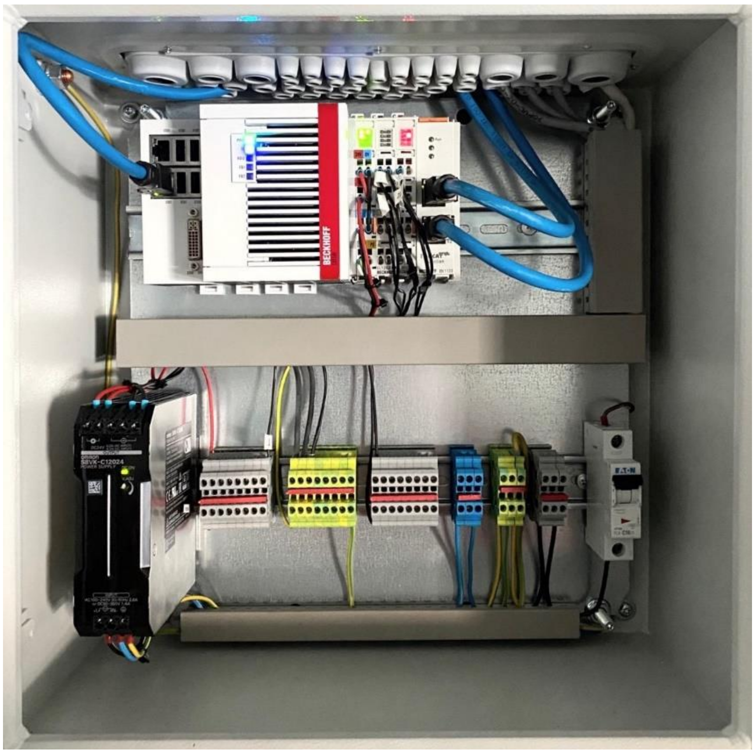


Figure A5.1. PMSC1 – Production monitoring system cabinet 1

Figure A5.2. PMSC2 – Production monitoring system cabinet 2

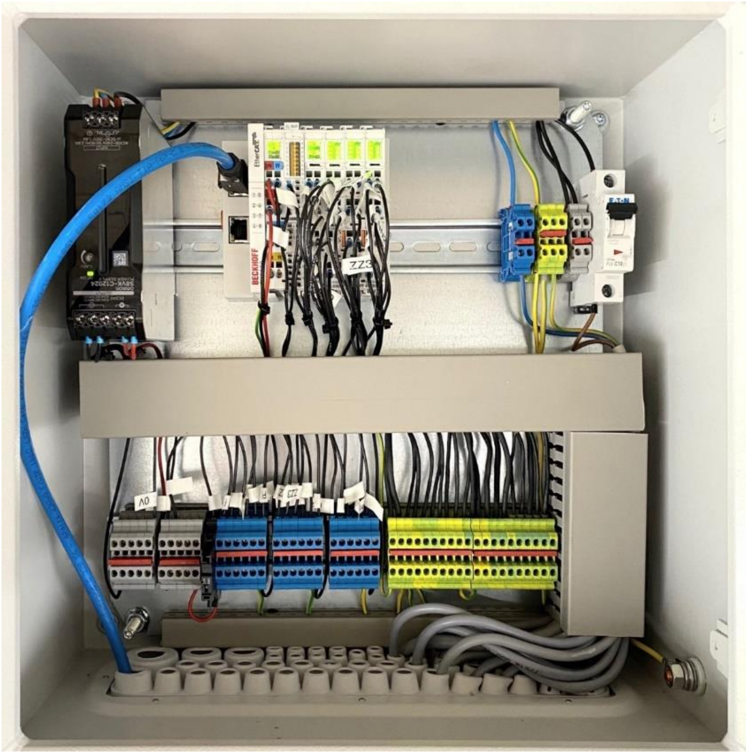


Figure A5.3. PMSC3 – Production monitoring system cabinet 3

Appendix 6 – Example structure for configuration data

```
TYPE ST_WMCurrent_2DTime_IN :
STRUCT

sEquipmentName           : STRING; // Name of the equipment
e_MMode                  : E_MonitorMode;  // Selected monitoring mode
fThresholdValueManual    : REAL;   // Threshold for manual monitoring
fThresholdValueAuto      : REAL;   // Threshold for auto. monitoring
fThresholdStdDev         : REAL;   // Threshold for std.dev. monitoring

bCalibrate               : BOOL;   // Calibrate command
fMarginAddedToThreshold  : REAL;   // Margin for calibration (0 - 100%)
bDisableMonitoring       : BOOL;   // Disable monoitoring, TRUE = disabled

nTimeBetween2cycles      : UDINT;  // Filtering time between 2 inputs
fThresholdForOffState    : REAL;   // Threshold value for  off-state

END_STRUCT
END_TYPE
```

Appendix 7 – Structure schematics of monitoring algorithms

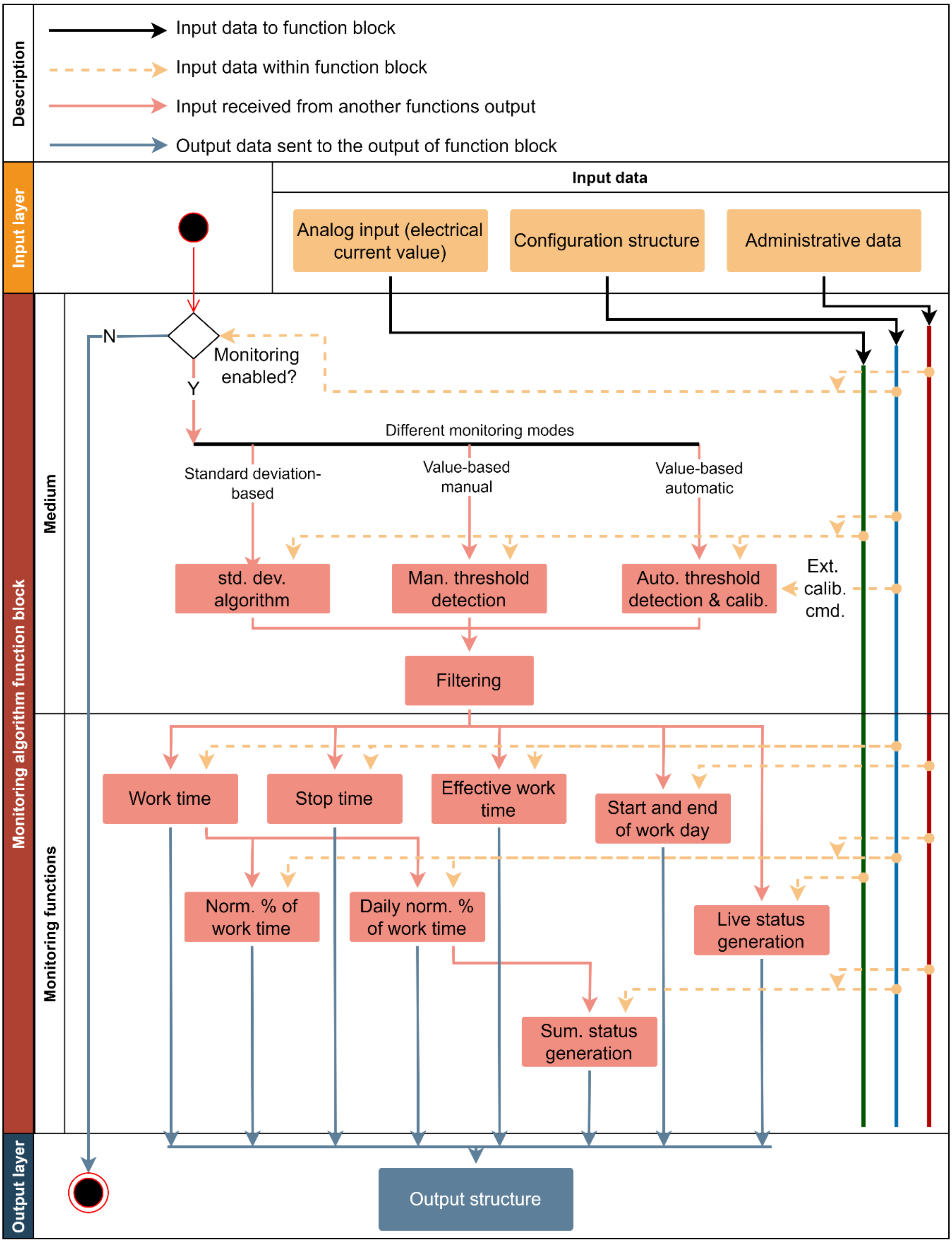


Figure A7.1. High-level structure diagram of electrical current-based production monitoring algorithm for sewing machines

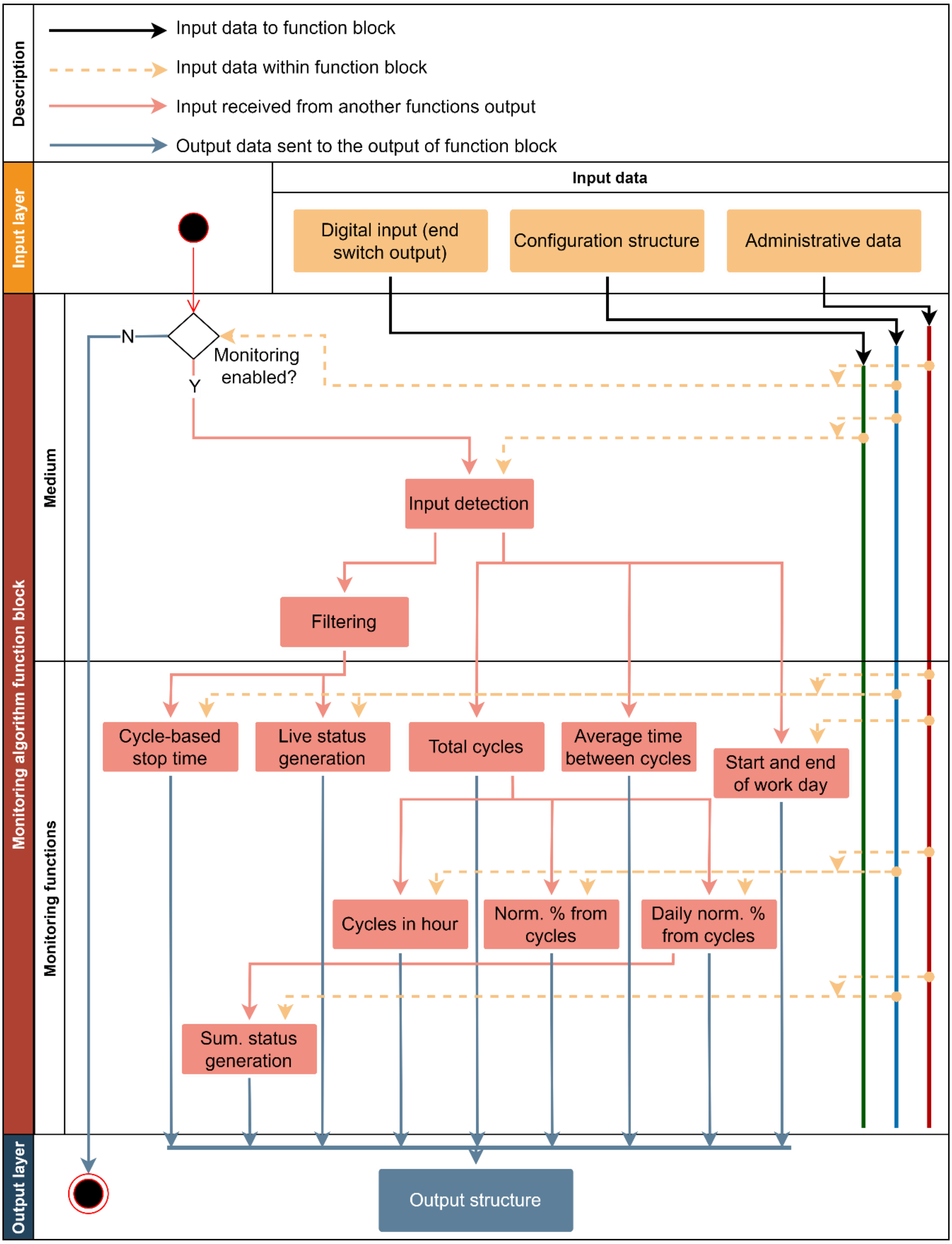


Figure A7.2. High-level structure diagram of binary input-based production monitoring algorithm for stamping machines

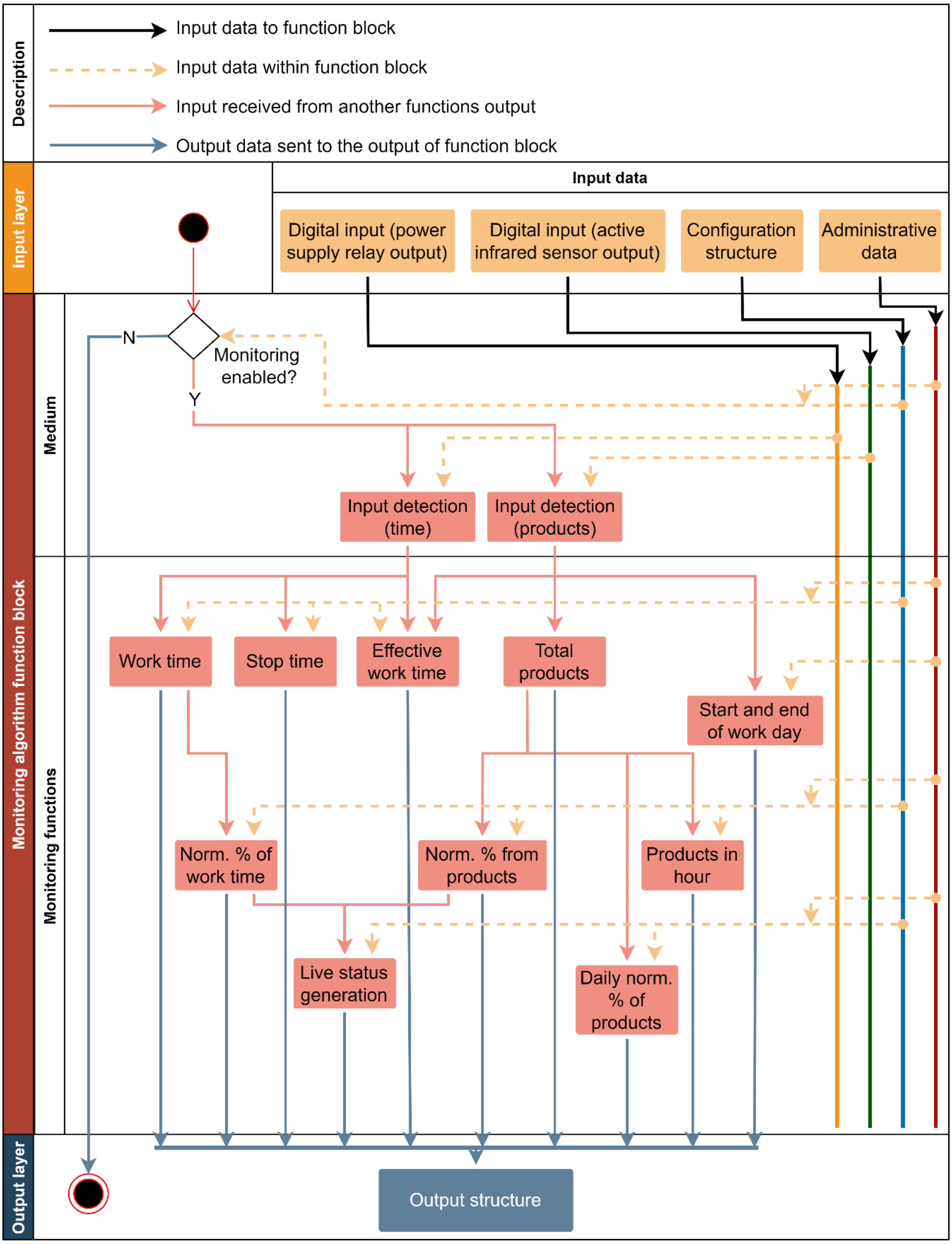


Figure A7.3. High-level structure diagram of production monitoring algorithm with two binary inputs for assembly line

Appendix 8 – Structure schematic of maintenance management

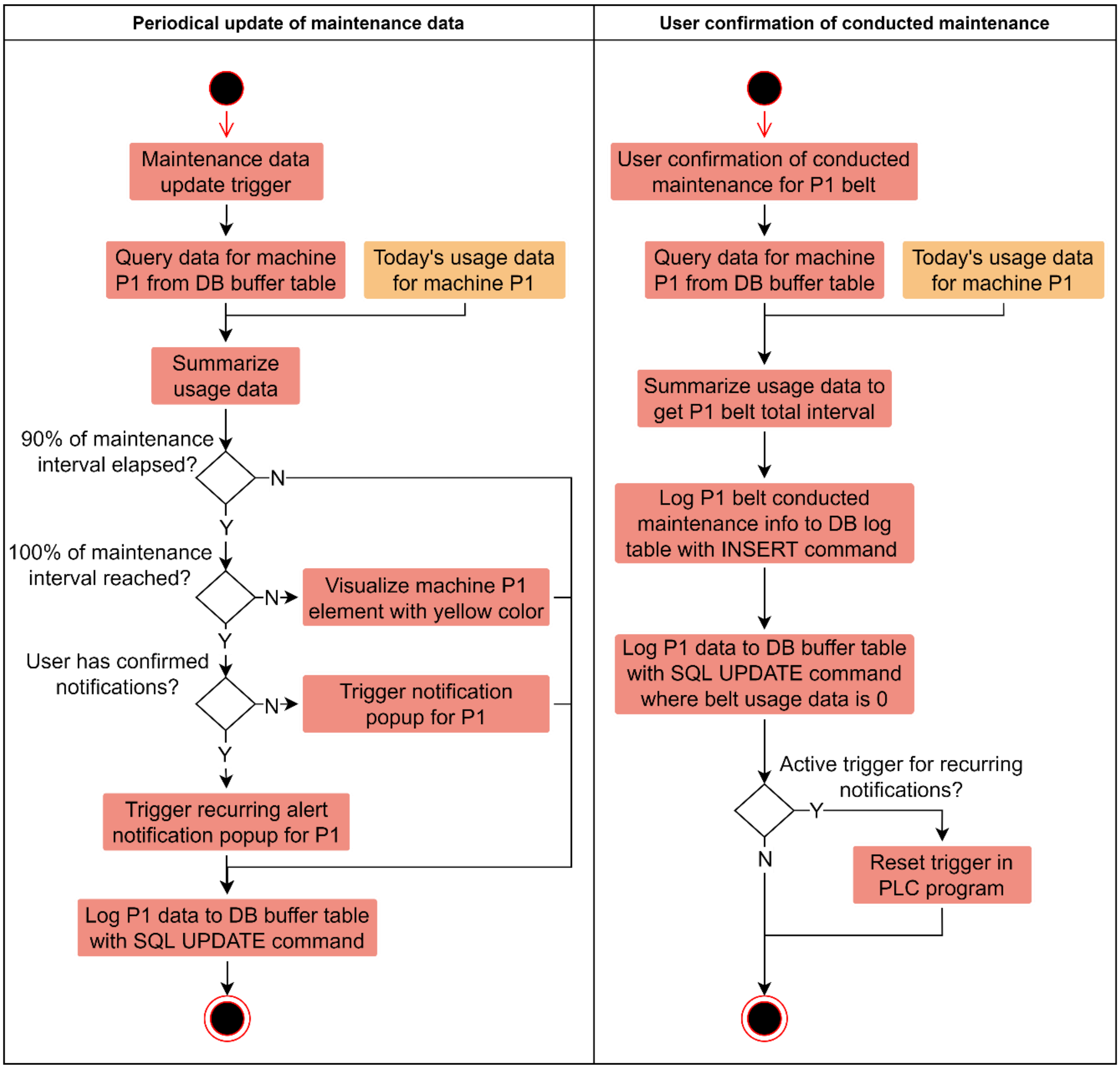


Figure A8.1. Structure schematic of usage-based maintenance management execution principles (note: schematics are composed using machine P1 and its belt maintenance confirmation as an example)

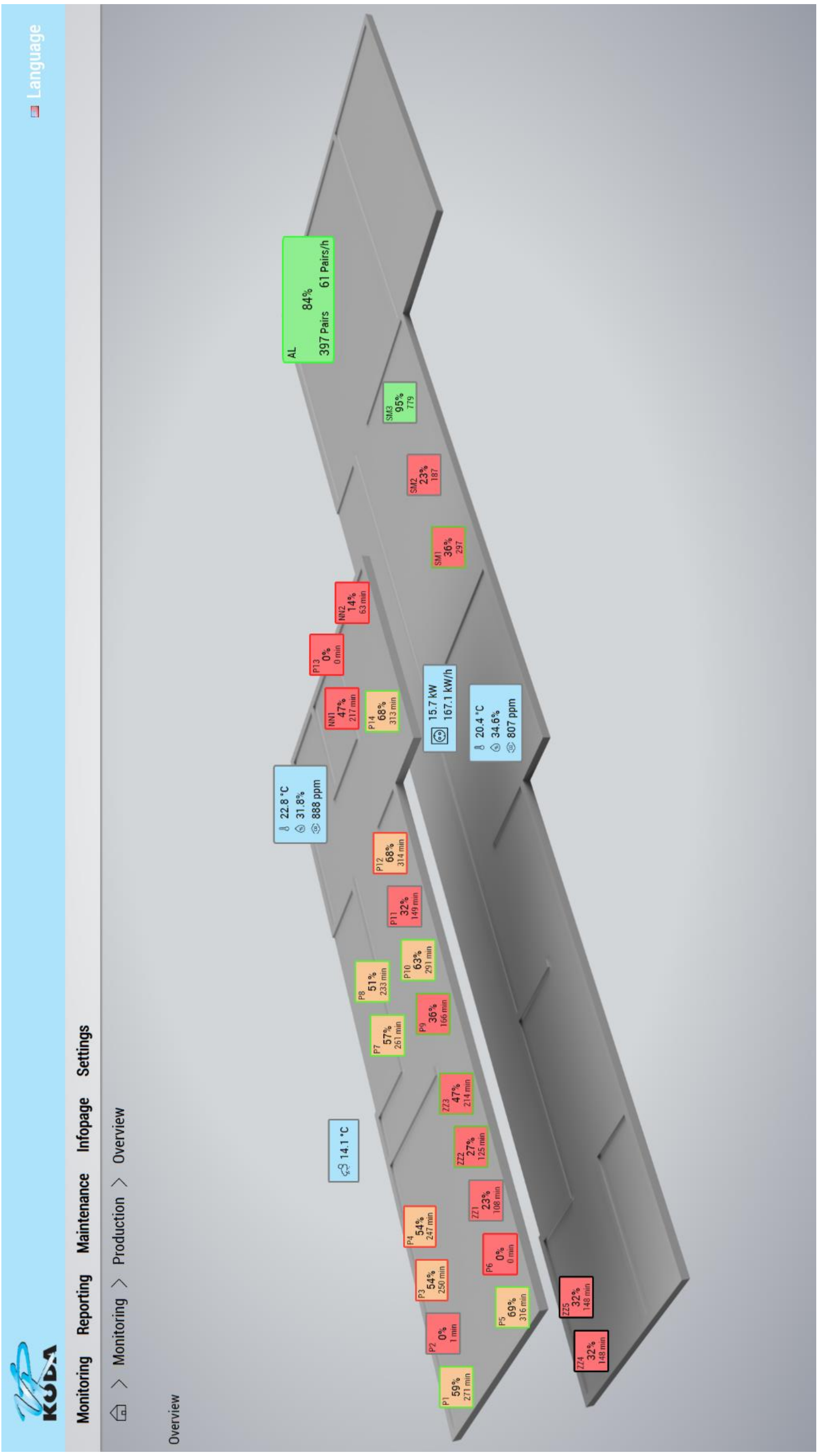


Figure A9.1 Main view of the visualization

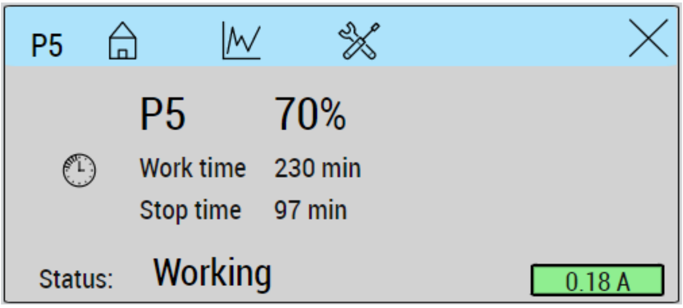


Figure A9.2. Main view of the popup for current-based monitoring of work time

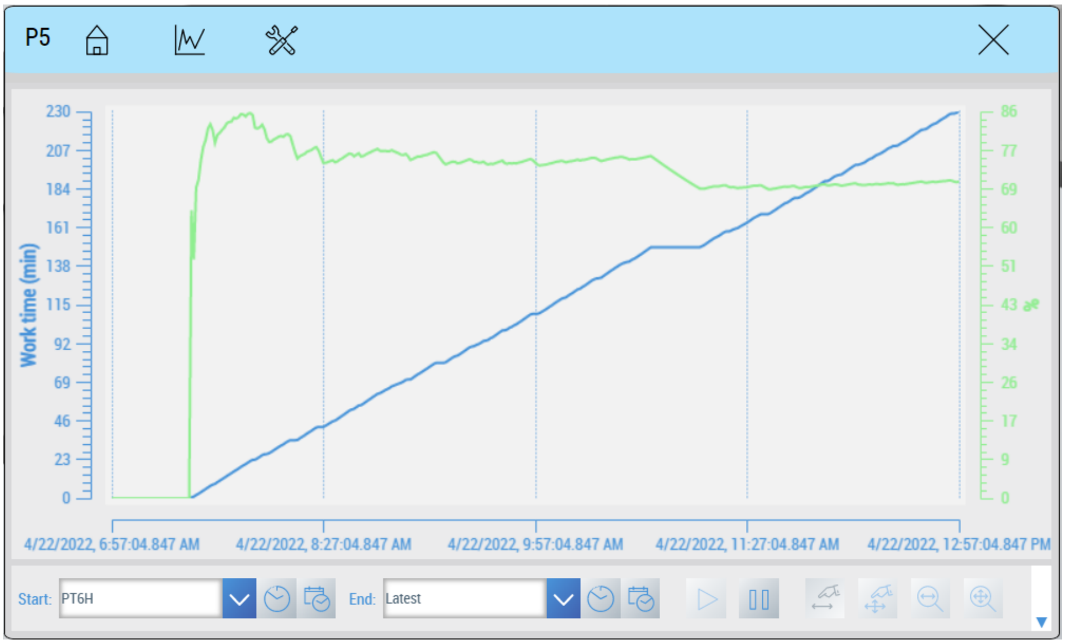


Figure A9.3. Graph view of the popup for current-based monitoring of work time

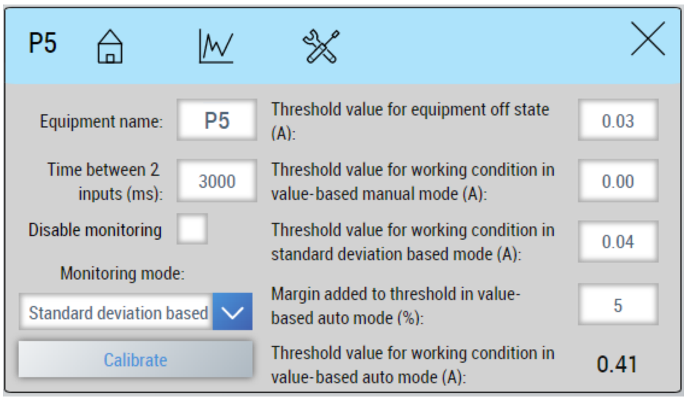


Figure A9.4. Configuration view of the popup for current-based monitoring of work time

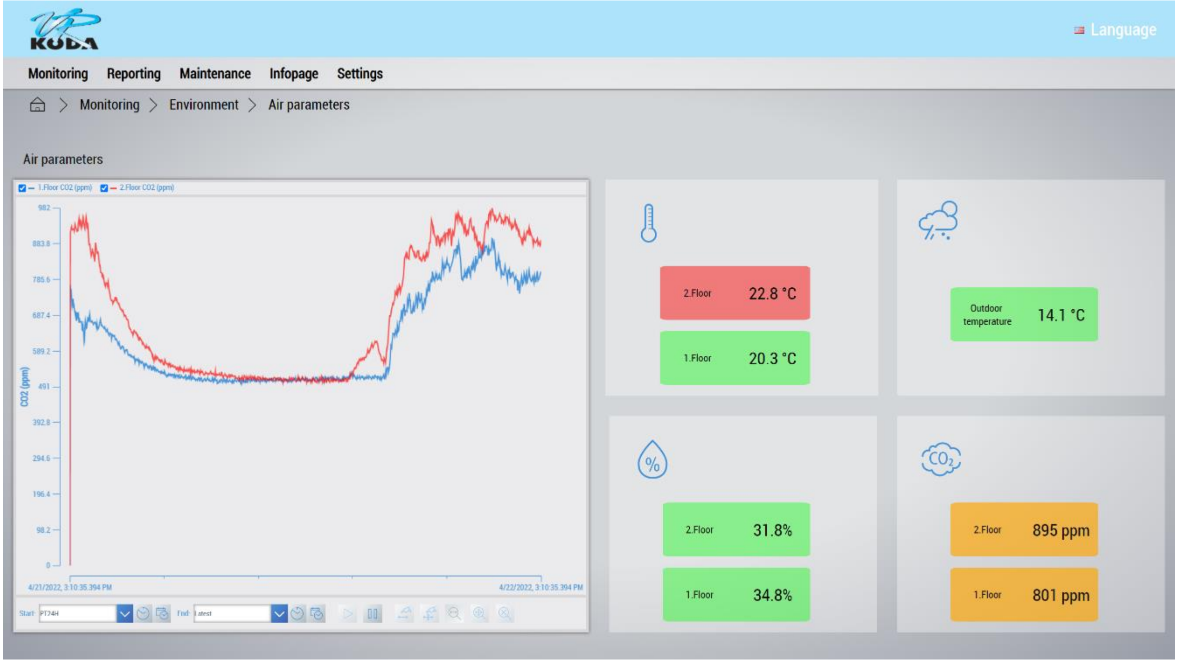


Figure A9.5. Environment monitoring dedicated view

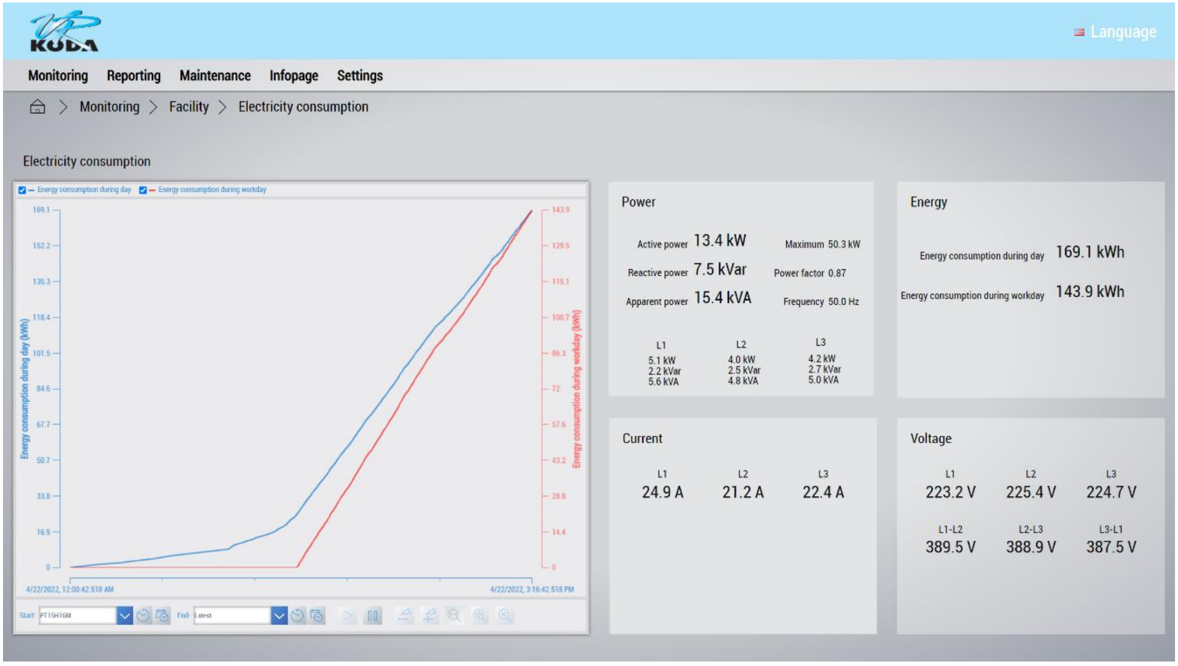


Figure A9.6. Facility monitoring electrical supply dedicated view

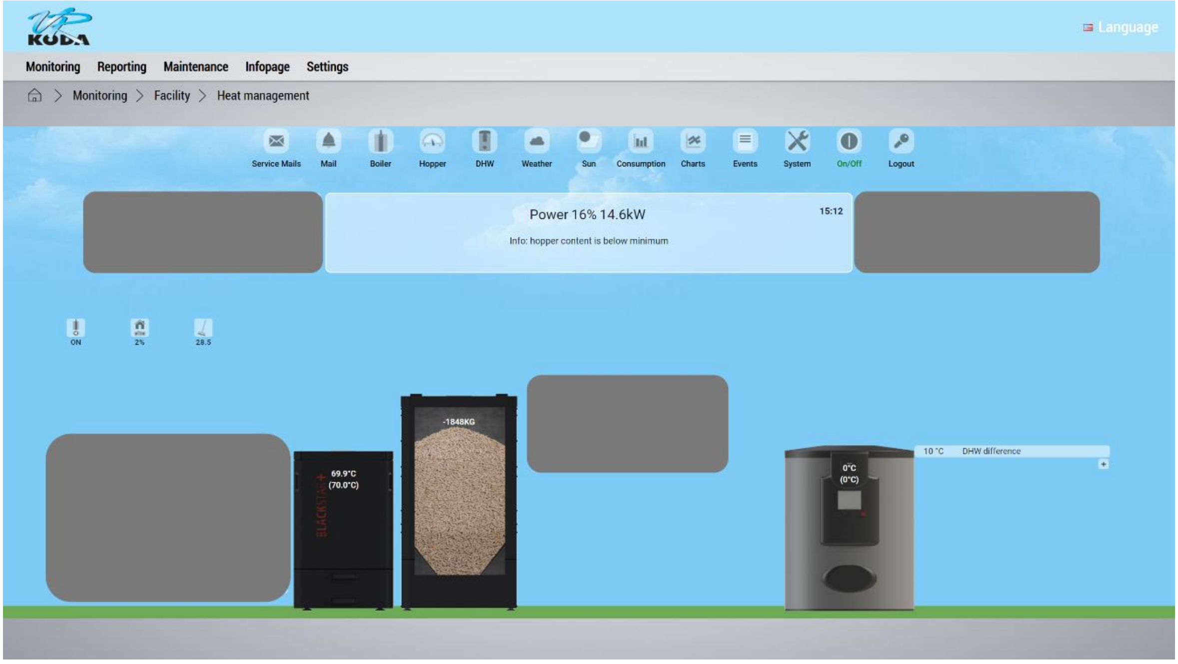


Figure A9.7. Facility monitoring heat management (extension utilizing heating system' web interface) dedicated view (sensitive information is covered)

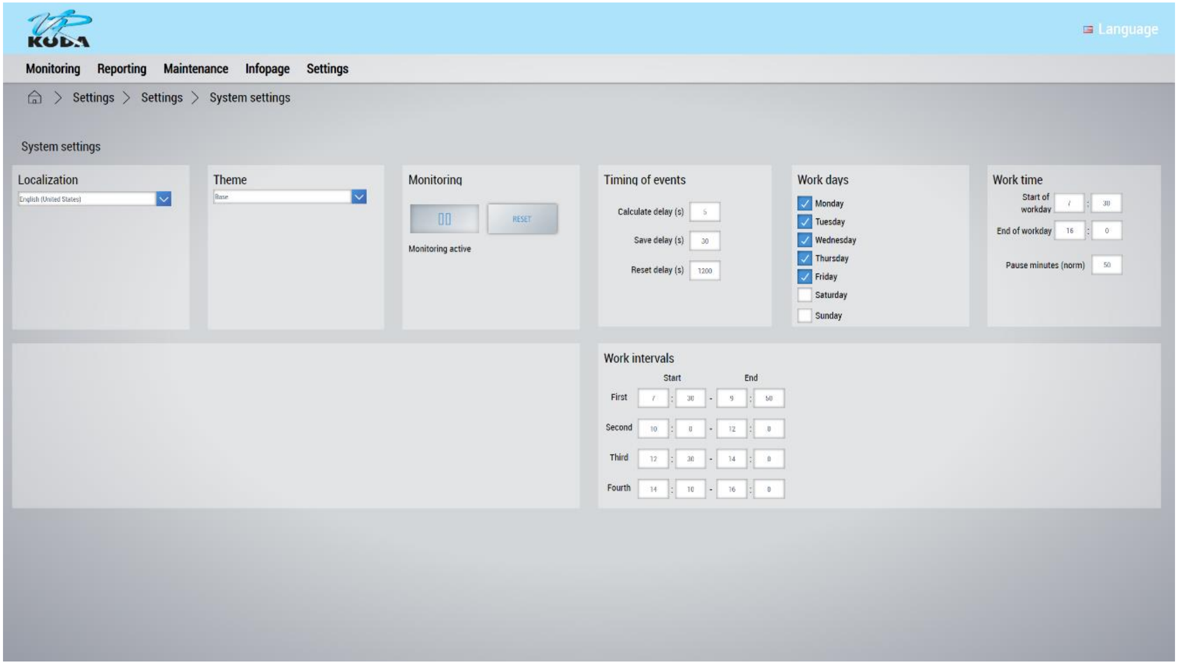


Figure A9.8. System settings view

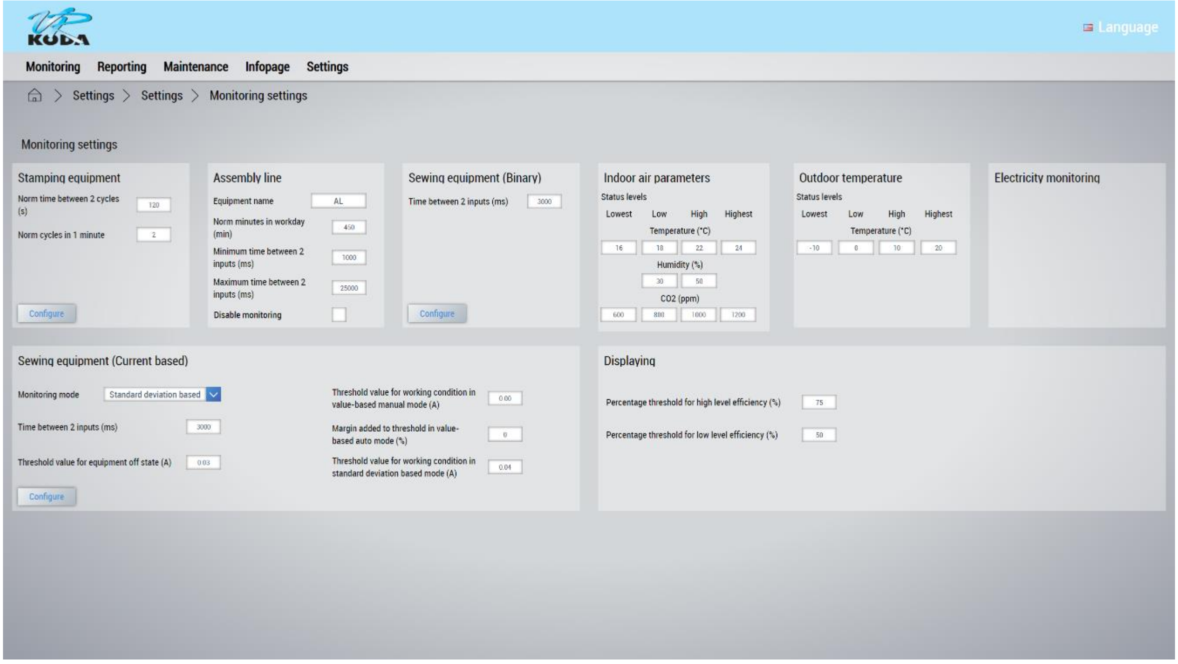


Figure A9.9. Monitoring settings view

Appendix 10 – Daily production monitoring report

28/04/2022 16:00:01

KODA

Päevaraport

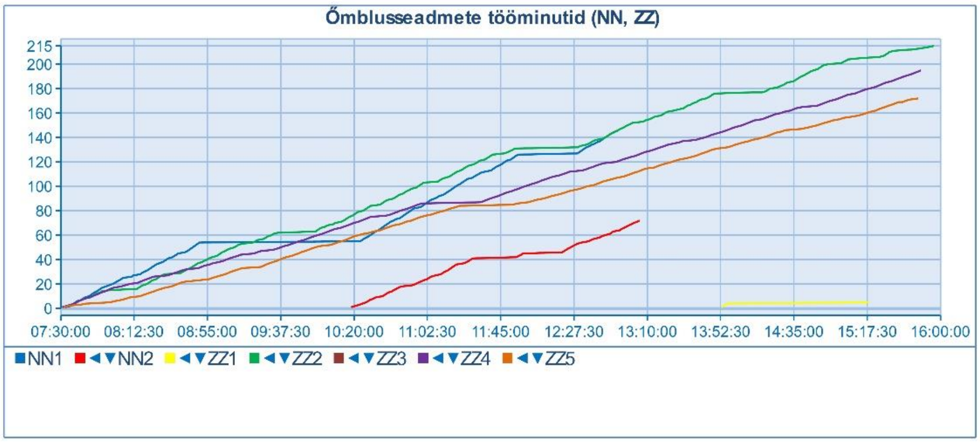
Toodetud paaride arv	580.00
Summaarne efektiivsus	58.3 %

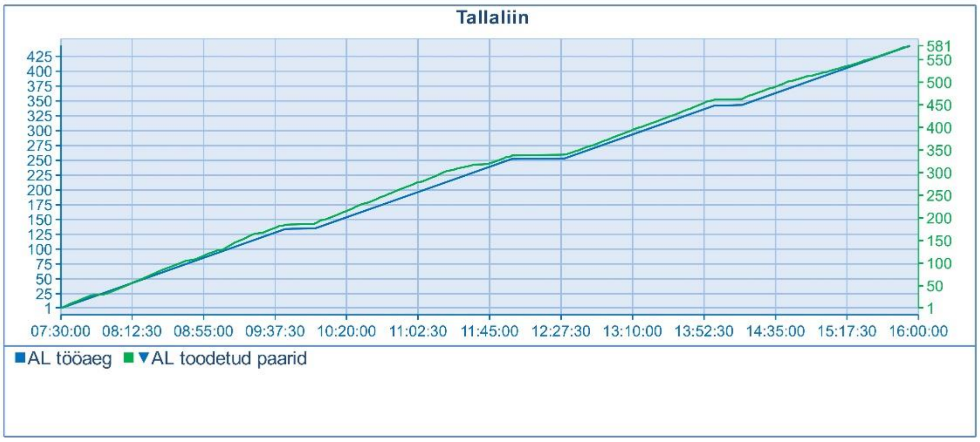
Seade	Töötsüklid	Protsent	Esimene tsükkel	Viimane tsükkel
SM1	398	43.3 %	28/04/2022 07:34:45	28/04/2022 15:57:58
SM2	303	32.9 %	28/04/2022 07:33:46	28/04/2022 15:55:58
SM3	658	71.5 %	28/04/2022 07:43:37	28/04/2022 15:57:45
AL toodetud paarid	580	126.1 %	28/04/2022 07:30:09	28/04/2022 15:55:03
Seade	Tööminutid	Protsent	Esimene minut	Viimane minut
P1	327	71.1 %	28/04/2022 07:30:48	28/04/2022 15:54:53
P2	354	77.0 %	28/04/2022 07:30:40	28/04/2022 15:51:23
P3	0	0	0	0
P4	275	59.8 %	28/04/2022 07:30:39	28/04/2022 15:54:42
P5	330	71.7 %	28/04/2022 07:32:19	28/04/2022 15:45:40
P6	238	51.7 %	28/04/2022 07:32:36	28/04/2022 15:53:36
P7	305	66.3 %	28/04/2022 07:30:48	28/04/2022 15:51:29
P8	270	58.7 %	28/04/2022 07:37:55	28/04/2022 15:51:51
P9	244	53.0 %	28/04/2022 07:30:43	28/04/2022 15:57:33
P10	351	76.3 %	28/04/2022 07:30:34	28/04/2022 15:58:44
P11	195	42.4 %	28/04/2022 07:30:52	28/04/2022 15:57:57
P12	386	83.9 %	28/04/2022 07:30:48	28/04/2022 15:57:20
P13	352	76.5 %	28/04/2022 07:30:39	28/04/2022 15:55:56
P14	295	64.1 %	28/04/2022 07:36:36	28/04/2022 15:52:31
NN1	146	31.7 %	28/04/2022 07:32:44	28/04/2022 12:53:18
NN2	72	15.7 %	28/04/2022 10:18:21	28/04/2022 13:05:35
ZZ1	5	1.1 %	28/04/2022 13:53:07	28/04/2022 15:18:33
ZZ2	215	46.7 %	28/04/2022 07:31:48	28/04/2022 15:56:06
ZZ3	0	0	0	0
ZZ4	195	42.4 %	28/04/2022 07:30:51	28/04/2022 15:48:46
ZZ5	172	37.4 %	28/04/2022 07:31:45	28/04/2022 15:47:00
AL tööaeg	443	98.4 %	28/04/2022 07:30:34	28/04/2022 15:54:59

1

Figure A10.1. Daily production monitoring report page 1

Figure A10.2. Daily production monitoring report page 2





3

Figure A10.3. Daily production monitoring report page 3

Appendix 11 – Weekly production monitoring report

29/04/2022 16:00:00

Nädalaraport

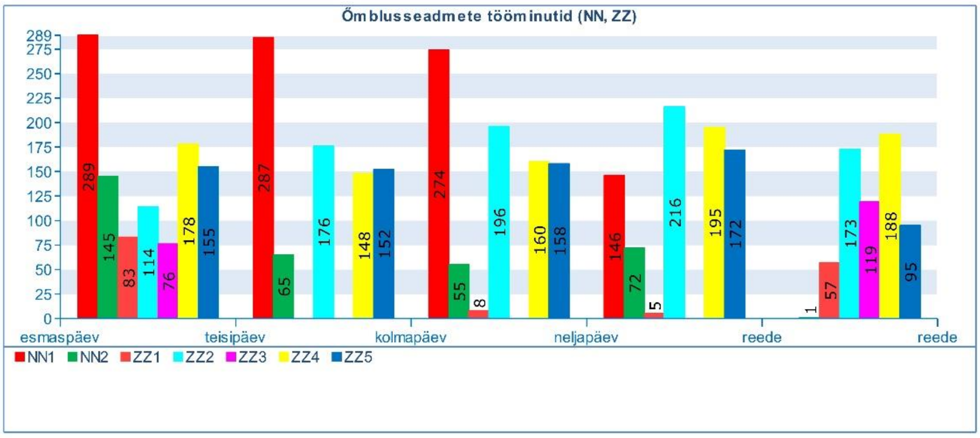
Toodetud paaride arv	2691
Summaarne efektiivsus	50.9 %

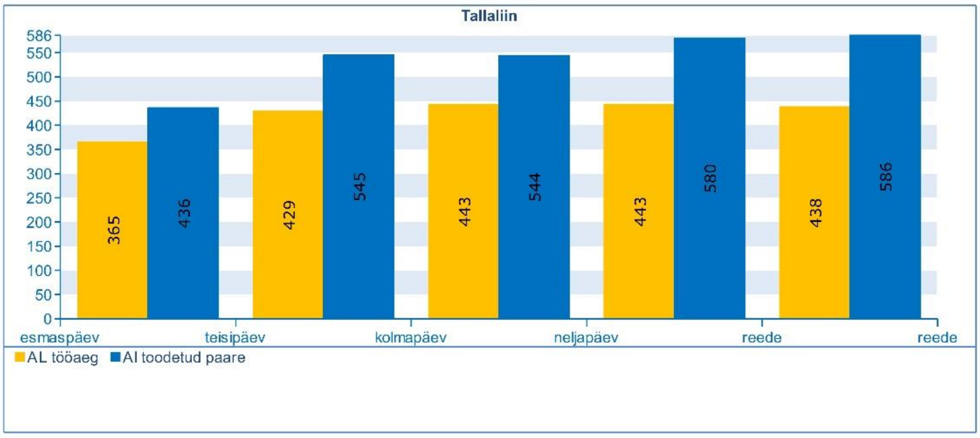
Seade	Töötsüklid	Protsent	Maksimum
SM1	1251	27.2 %	398
SM2	2147	46.7 %	558
SM3	2492	54.2 %	658
AL toodetud paarid	2691	117.0 %	586
Seade	**Tööminutid**	**Protsent**	**Maksimum**
P1	1487	64.7 %	327
P2	1314	57.1 %	354
P3	669	29.1 %	282
P4	1335	58.0 %	306
P5	1654	71.9 %	360
P6	710	30.9 %	261
P7	1387	60.3 %	305
P8	1366	59.4 %	301
P9	1086	47.2 %	244
P10	1609	70.0 %	352
P11	969	42.1 %	202
P12	1805	78.5 %	386
P13	1474	64.1 %	352
P14	1587	69.0 %	357
NN1	996	43.3 %	289
NN2	338	14.7 %	145
ZZ1	153	6.7 %	83
ZZ2	875	38.0 %	216
ZZ3	195	8.5 %	119
ZZ4	869	37.8 %	195
ZZ5	732	31.8 %	172
AL tööaeg	2118	94.1 %	443

1

Figure A11.1. Weekly production monitoring report page 1

Figure A11.2. Weekly production monitoring report page 2





3

Figure A11.3. Weekly production monitoring report page 3

Appendix 12 – Web report

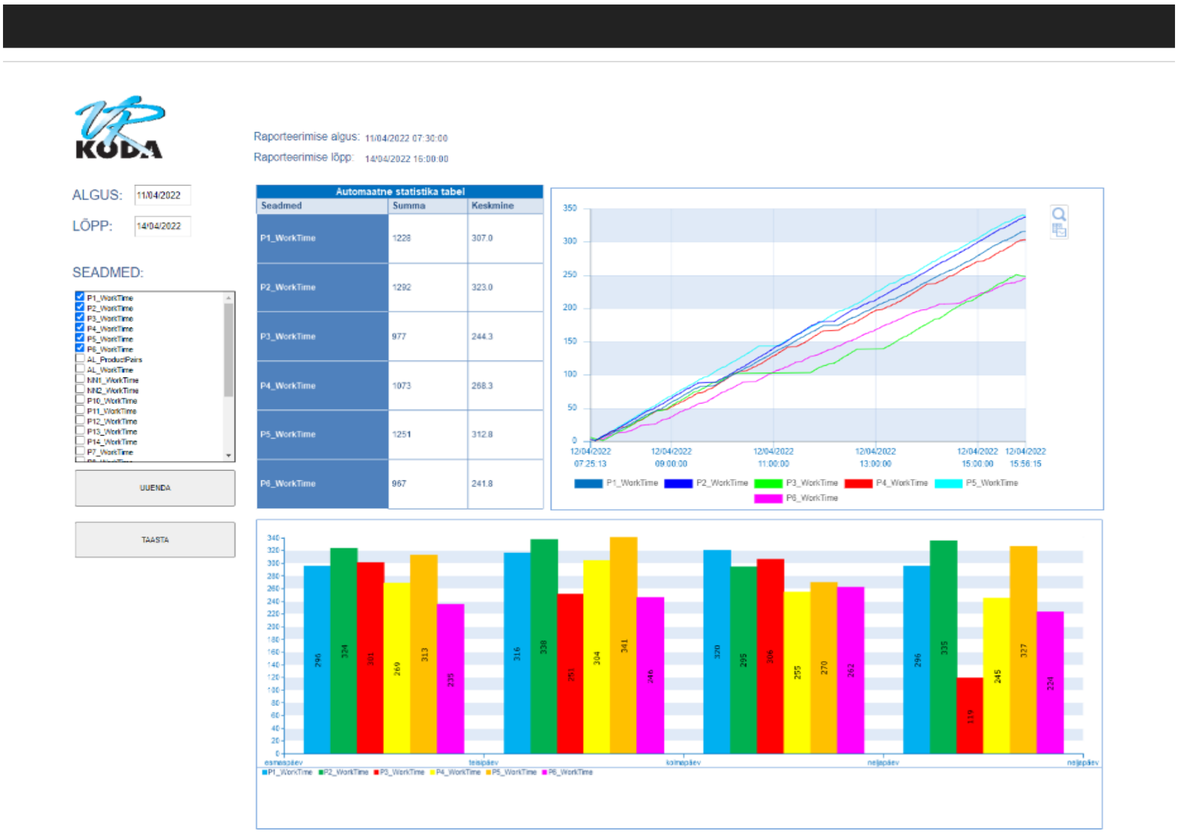


Figure A11.1. Example of web report containing work time data from six sewing machines (note: interactive line chart is zoomed in to one specific workday of the selected period)