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Ozan Yesilyurt

# »Approach development for enabling energy flexibility in manufacturing companies with AGV lithium batteries through an algorithm-based ICT solution«

Fraunhofer IPA

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**Ozan Yesilyurt, M.Sc.**

# » Approach development for enabling energy flexibility in manufacturing companies with AGV lithium batteries through an algorithm-based ICT solution«

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# Approach development for enabling energy flexibility in manufacturing companies with AGV lithium batteries through an algorithm-based ICT solution

**Von der Fakultät Energie-, Verfahrens- und Biotechnik**
**der Universität Stuttgart**
**zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.)**
**genehmigte Abhandlung**

**Vorgelegt von**

**Ozan Yesilyurt**
**aus Beyoglu**

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# Preface

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Stuttgart, 08.01.2024 Ozan Yesilyurt

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# Index of Abbreviations

| | |
|---|---|
| AB | Agent-based |
| AGV | Automated guided vehicle |
| AGVS | Automated guided vehicle systems |
| API | Application Programming Interface |
| BMUC | Battery manufacturing use case |
| BSS | Battery storage systems |
| BUOS | Battery usage optimization service |
| CIM | Computer integrated manufacturing |
| CMUC | Chemicals manufacturing use case |
| CPS | Cyber-physical systems |
| CS | Charging station |
| DB | Database |
| DE | Discrete event |
| DSM | Demand-side management |
| DOD | Depth of discharge |
| DR | Demand response |
| EFDM | Energy flexibility data model |
| EFMS | Energy flexibility management service |
| ESP | Energy synchronization platform |
| ESS | Energy storage system |

| | |
|---|---|
| EU | European Union |
| EV | Electric vehicle |
| FMS | Flexible manufacturing system |
| FTS | Fahrerlose Transportsysteme |
| GA | Genetic algorithm |
| GUI | General user interface |
| ICT | Information and communication technologies |
| IP | Internet protocol |
| IRR | Internal rate of return |
| ISA | International Standards of Automation |
| IT | Information technology |
| LCO | Lithium cobalt oxide |
| LFP | Lithium iron phosphate battery |
| MDCS | Charging station with minimum delay |
| MES | Manufacturing Execution System |
| MSB | Manufacturing Service Bus |
| MVC | Model view controller |
| NCS | Nearest charging station |
| NiCd | Nickel-cadmium |
| NiMH | Nickel-metal hydride battery |
| NPV | Net present value |
| PMUC | Plastics manufacturing use case |
| PSO | Particle swarm optimization |

| | |
|---|---|
| PV | Photovoltaic |
| RAMI 4.0 | Reference Architectural Model Industry 4.0 |
| REST | Representational State Transfer |
| ROI | Return of investment |
| SD | System dynamics |
| SOA | Service-oriented architecture |
| SOC | State of charge |
| TCP | Transmission Control Protocol |
| UoM | Unit of measurement |
| UT | Unit test |
| VM | Virtual machine |

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# Kurzbeschreibung

Produzierende Unternehmen sind derzeit mit einem komplexen Umfeld für ihre Fabriken konfrontiert, was die aktuelle und künftige Energieversorgung betrifft. Die Unternehmen sollten die Stromkosten auf der Grundlage von zwei Messwerten bezahlen. Der eine ist der Energieverbrauch des produzierenden Unternehmens, der andere der Spitzenbedarf. Die Stromlieferanten vereinbaren mit den Unternehmen vertraglich Preismodelle, die sich an der höchsten Produktionslastspitze orientieren. Die produzierenden Unternehmen sind mit diesen Lastspitzen in ihrer Produktion konfrontiert und zahlen aufgrund der Erzeugung von Spitzenlasten hohe Beträge. Daher wurden verschiedene Konzepte und Anwendungen von Energiespeichersystemen, wie stationäre Batterien und Batterien für Elektrofahrzeuge (EV), untersucht und entwickelt, um Lastspitzen zu minimieren und die Einsparungen für die Unternehmen zu erhöhen.

Fahrerlose Transportsysteme (FTS) können als elektrische Energiespeicher in produzierenden Unternehmen betrachtet werden. Laut der Studie von BIS Research werden die Batteriekapazität und die Produktion von elektrisch betriebenen FTS in den nächsten drei Jahren zunehmen. Im Jahr 2025 wird es weltweit etwa 273.000 in Betrieb befindliche FTS geben. Diese hohe Anzahl von FTS bietet eine große Batteriekapazität, die für Energieflexibilisierungsmaßnahmen wie die Laststeuerungsmethode Peak Shaving in Fertigungsunternehmen genutzt werden kann. Darüber hinaus ist der Einsatz von FTS in Produktionsbetrieben für 78% der deutschen Unternehmen relevant. Darüber hinaus zeigt die Studie, dass 64% der Unternehmen an der Integration von Energiespeichern in ihren Betrieben arbeiten.

FTS-Batterien können dazu verwendet werden, Spitzenlasten abzufangen und die Stromkosten für Unternehmen zu senken. Um dies zu realisieren, benötigen FTS-Batterien eine intelligente Lade- und Entladeplanung. Diese Dissertation stellt eine Softwarelösung vor, die Energieflexibilität in der Produktion mit FTS-Batterien ermöglicht. Zunächst werden die allgemeinen Anforderungen und Anwendungsfälle dargestellt und mit den bestehenden

Forschungsansätzen verglichen, um die Herausforderungen und wissenschaftlichen Lücken bei der Entwicklung eines generischen Ansatzes zu ermitteln. Anschließend wird ein generischer Ansatz für die Nutzung von FTS-Batterien als Energiespeicher entwickelt, so dass die Lastspitzen in Produktionsunternehmen durch den Einsatz von FTS-Batterien reduziert werden können. Der generische Ansatz wird durch einen "Batterienutzungsoptimierungsservice" instanziiert, um seine Machbarkeit zu beweisen.

Die Softwarelösung optimiert die Energiespeicherung in drei Schritten: Im ersten Schritt werden die optimalen Lade- und Entladepunkte anhand des Energieverbrauchs, der erneuerbaren Energieerzeugung und der Strompreise während der Produktion berechnet. Im folgenden Arbeitsschritt werden die Daten der FTS-Routen, der FTS-Batteriekapazität, die FTS-Lade-, Arbeits- und Leerlaufzeiten verwendet, um die Verfügbarkeit der FTS zu ermitteln. Ein Entscheidungsmechanismus für die Lade- und Entladeplanung legt schließlich fest, wann die FTS-Batterie unter Berücksichtigung der Batteriedegradation, der Verfügbarkeit der FTS und der Belegung der Ladestationen geladen und entladen werden soll, ohne die bestehende Produktionssituation negativ zu beeinflussen.

Die Vorteile und das Potenzial des Einsatzes von FTS als Energiespeicher zur Reduzierung von Lastspitzen in einem Unternehmen werden veranschaulicht, nachdem eine Sensitivitätsanalyse mit den von der Softwarelösung berechneten Ergebnissen in drei verschiedenen Anwendungsszenarien durchgeführt wurde.

Die Ergebnisse der Sensitivitätsanalyse zeigen, dass der Einsatz von FTS-Batterien als Energiespeicher zur Minimierung von Lastspitzen für die betrachteten Produktionsunternehmen unter bestimmten Bedingungen, wie der Verfügbarkeit von FTS-Batterien und der Anzahl der Ladevorgänge, vorteilhaft sein kann.

# Abstract

Manufacturing companies are currently dealing with a complex environment for their factories concerning current and future energy supply. The companies should pay electricity costs based on two readings. One is for the manufacturing company's energy consumption, and the other is for peak demand. The electricity suppliers contractually arrange pricing models with the companies based on the highest peak production load. Manufacturing companies face these load peaks in their manufacturing and pay high amounts of money because of the generation of peak loads. Therefore, different concepts and applications of energy storage systems, such as stationary and electric vehicle (EV) batteries, were studied and developed in manufacturing plants to minimize peak loads and enhance savings for the companies.

Automated Guided Vehicles (AGV) can be considered electrical energy storage in manufacturing companies. According to the BIS Research’s study, the battery capacity and production of electrically powered AGVs will increase over the next three years. There will be approximately 273,000 operating AGVs worldwide in 2025. This high number of AGVs offers a large battery capacity that can be used for energy flexibility measures such as the load control method peak shaving in manufacturing companies. In addition, AGV usage in manufacturing plants is relevant for 78% of German companies. Moreover, the study shows that 64% of the companies are involved in integrating energy storage in their companies. This shows that AGVs offer great potential as transport vehicles and energy storage for manufacturing companies.

AGV batteries can be used to enable peak shaving and to reduce electricity costs for companies. To realize this, AGV batteries require intelligent charging and discharging scheduling. This dissertation introduces a service for enabling energy flexibility in production with AGV batteries. First, overall and use case requirements are presented and compared to the existing research approaches to determine the challenges and scientific gaps in designing a generic approach. Then, the generic approach is created to use the AGV batteries as energy storage so that the peak loads in manufacturing companies can be reduced by using AGV batteries. The generic approach is instantiated through a “battery usage optimization service” to prove its feasibility.

The service optimizes energy storage through three steps: In the first step, optimal charging and discharging points are calculated using energy consumption, renewable energy generation, and electricity prices during production. In the following working step, the data of the AGV routes, the AGV battery capacity consumption, the AGV charging, working and idle times are used to find out the availability of the AGV. In the end, a decision mechanism for charging and discharging scheduling determines when the AGV battery should be charged and discharged in consideration of battery degradation, availability of the AGVs, and charging station occupancies without negatively affecting the existing production situation.

The benefits and potential of using AGVs as energy storage to reduce peak loads in a company are illustrated after a sensitivity analysis is performed with the calculated results by the service in three different use case scenarios.

The results of the sensitivity analysis show that using AGV batteries as energy storage to minimize peak loads can be beneficial for the considered manufacturing companies under certain conditions, such as the availability of AGV batteries and the number of charging stations in the companies and the used battery capacity of AGV batteries in this dissertation. As a future work, the developed service can be developed to investigate further whether it is economical to reduce electricity costs of manufacturing companies by trading electricity in the intraday market with the help of the AGV batteries.

# 1 Introduction

The introduction begins with the motivation for this work. Then the problem statements are introduced and objective target of this dissertation is presented. Finally, the scientific theoretical positioning and structure of this work are described.

## 1.1 Motivation

The United Nations General Assembly has defined 17 sustainability goals to ensure a long-term viable world community. According to the seventh of the sustainability goals, the share of renewable energies should be increased in the global energy mix (United Nations 2015, p. 14).

More than 150 countries decided to adopt their energy and set climate protection targets at the international climate conference in Paris in 2015 (European Parliament 2018, p. 1). As a result, the share of renewable energy should be achieved by at least 32% in the European Union (EU) in 2030 (European Parliament 2018, p. 1). Therefore, the German government has aimed to generate 65% of its power from renewable sources by 2030 (BMWi 2018, p. 5).

Electricity generation from renewable sources fluctuates significantly. Hence, the energy demand must be flexibly regulated to compensate for the power grid. This process is known as Demand-Side Management (DSM) and, in particular, as Demand Response (DR) (Roesch et al. 2019, p. 2). DG ENER’s working paper (ENER 2016, p. 1) explains energy storage's future role and challenges. According to this paper, energy storage will be essential in providing excellent energy supply security even with a more fluctuating supply.

It is common for manufacturing companies to have special electricity tariff models that include basic, labor, and reactive power and electricity prices. This is often a substantial cost factor of electrical energy for companies and depends on the highest peak production load. Therefore, different concepts and applications of energy storage systems (ESS) were studied and developed in manufacturing plants to minimalize peak loads and enhance savings for the companies (see chapter 3.1).

In this work, only the electrical energy storage devices of the AGV are considered to achieve the same goal because, according to the study BIS Research (2022), the battery capacity and production of electrically powered AGVs will increase over the next three years, and there will be approximately 273,000 operating AGVs worldwide in 2025. This high number of AGVs offers a large battery capacity (approximately 6.8 GWh), calculated as an average value with the help of the battery capacities of the AGVs ranging from three kWh for small AGVs to 48 kWh for AGV forklifts. This can be used for energy flexibility measures such as the load control method peak shaving in manufacturing companies. In addition, 78 % of German companies use AGVs in their production facilities and are prepared to invest in the development of planned energy flexibility measures (Bundesvereinigung Logistik 2018). The employees of 64 % of the companies are involved in the integration of energy storage in their companies, according to the study Zimmermann et al. (2019, p. 76). This shows that AGVs offer great potential as transport vehicles and energy storage for manufacturing companies.

## 1.2 Problem Statement

Manufacturing companies face a difficult situation with their factories regarding current and future energy supply. Rising electricity prices, caused by crises and the Ukraine war, are leading to energy supply problems for companies. Therefore, they are forced to use the energy effectively. The companies are charged for electricity based on two readings. One is for energy consumption, and the other is for peak demand. Besides the energy consumption contracts, the companies must agree with the electricity providers on contractual price models depending on the highest peak production load.

Manufacturing companies experience peak loads in their production and pay high amounts of money for generating peak loads (Kurnik et al. 2017, p. 2). Because the fluctuations on the power grid affect the grid stability and additional fossil fuel-powered plants, such as diesel or open-cycle gas/hydro turbines plants, which have high operating costs, but are quickly activated (Ganu et al. 2012, p. 1), should be put into operation to balance the grid. In the last years, the costs of activating gas turbine plants are additionally increased according to the Ukraine war and gas shortage in Europe, which directly increases electricity prices.

The peak loads are often caused by operating the manufacturing facilities when the companies have to produce more products because of the high number of orders. Besides the manufacturing operations, the logistic factors should also be considered because companies are investing more in battery-powered AGVs, which can increase companies' power consumption. According to (BIS Research 2022), the number of AGVs is increasing, and there will be operating AGVs in manufacturing plants in 2025, two times more than in 2020. Due to the increasing number of AGVs, the energy demand of the companies will be increased, which can be caused peak loads and high electricity costs for the companies. Additionally, it must still be taken into account to provide intelligent charging scheduling for the AGV batteries. The uncoordinated charging of the AGV batteries can also cause peak loads and high electricity costs for the companies.

According to the research of Gils (2014, p. 8), the average reduction percentage for peak loads lies between 20 and 25 % in non-EU countries and 15 % EU-wide in the industry sector. Therefore, new solutions for peak load reduction are required to use this high potential. To solve this problem, this work examines to what extent mobile electrical energy storage devices such as AGV batteries can reduce peak loads and cost-effectively consume electricity in companies. The next chapter describes the objective target in detail.

## 1.3 Objective Target

The scientific objective target of this dissertation is to

**develop an optimization approach for realizing energy flexibility in production with AGV lithium batteries using the estimated production data by an algorithm-based information and communication technologies (ICT) solution.**

The generic approach is instantiated through the ICT solution "battery usage optimization service" to prove its feasibility. With using this solution, it is targeted to optimize the usage (charging and discharging schedule) of AGV batteries during the ongoing production to enable a cost-effective coverage of some of the production energy loads (peak shaving). This solution also enables energy-flexible behavior in the future 'companies' power system and reduces electricity costs for companies. In the context of this work, an algorithm was developed, which was embedded into an ICT solution that calculates the optimal charging and discharging times of AGV batteries to reduce peak loads in the companies. In this work, the software has been developed to show the possible optimization level of the AGV batteries by adjusting charging and discharging schedule of the AGV batteries and validated how much cost savings the companies can make with the help of this software during the peak loads of its industrial grid. The ICT solution does not cover hardware development. It is a pioneer work in this field and investigated in different use cases whether the AGV batteries can economically cover the peak loads in the companies.

## 1.4 Scientific Theoretical Positioning

Science (see Figure 1.1) is divided into real and formal science, according to Ulrich et al. (1976, p. 305). The formal sciences deal with the construction of sign systems and the rules for using these signs. Mathematics, logic, and philosophy provide an example of the formal sciences.

According to Ulrich et al. (1976, p. 305), real science is divided into two categories. They are so-called strictly basic sciences and applied practical sciences. The strictly basic sciences focus on theoretical objectives and attempt to explain empirical reality segments. The natural sciences can be given as an example of the strictly basic sciences. In contrast, applied practical sciences, such as social and engineering sciences, endeavor to analyze human action alternatives and achieve practical goals.

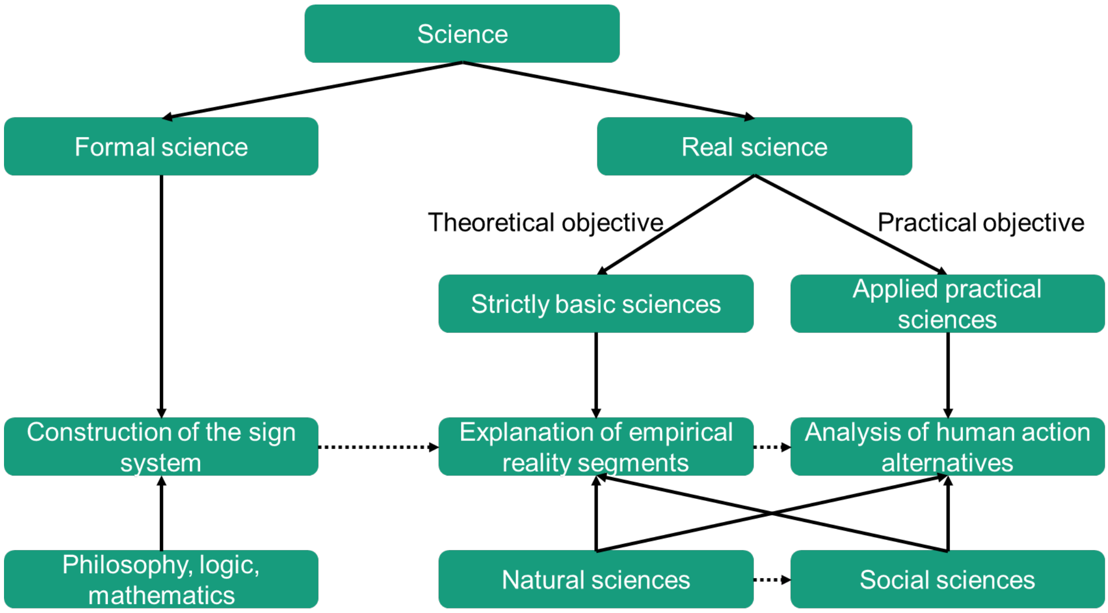



Figure 1.1: Theoretical scientific positioning according to (Ulrich et al. 1976, p. 305)

The procedure of the scientific approach of Ulrich et al. (1976, p. 305) offers a helpful framework for classifying this scientific work. The problem statement of this dissertation can be placed in the technical sciences, whereas methods from the formal sciences are also used for the solution. To reduce peak loads in manufacturing companies, an ICT solution is developed in this dissertation, which develops decision models for AGV batteries using different algorithms modeled in a software code. In parallel, however, mathematics and logic from formal science are required to create these algorithms. Therefore, the presented work is regarded as a result of the problem reference to practice and a practice-oriented, applicable method of applied research. The application context is the focus of this work. Hence, this work is positioned under the applied practical sciences.  Ulrich et al. (2001, pp. 21–40) answers the question of the approach to applied research with a research-methodical phase concept. This dissertation adheres to applied research; hence, the research-methodical phase must indicate the dissertation structure.

## 1.5 Structure of the Dissertation

This dissertation's research process and structure are based on the applied research approach Ulrich et al. (2001, pp. 21–40), which focuses on the importance of practical relevance in the research process. Figure 1.2 depicts the dissertation structure.

**Chapter 2** gives an overview of the state of the art. In this chapter, the relevant technical terms are defined and categorized in different areas, such as energy, IT, hardware, and models.

The existing research approaches are introduced in **Chapter 3** in three application categories. Therefore, it is categorized under the third and fourth phases of applied research because the problem-relevant procedures, such as peak shaving applications with different battery technologies, are shown, and the relevant application context is mentioned in this chapter. Additionally, the existing AGV simulation concepts are described, which are relevant for the simulation development of AGV batteries in this dissertation. To generate the required AGV data for the ICT solution, the simulations are developed for the use cases (companies) according to their logistic plan realistically, which can be easily customized to new companies and could also be used in greenfield environments.

The overall and use case requirements are specified for the ICT solution, and the overall concept of the ICT solution is presented in **Chapter 4**. Then, the scientific gap is identified by comparing the existing research solution approaches with the defined requirements. That is why this chapter considers the problem-relevant procedures phase of the applied research, such as peak shaving applications with different battery technologies, to find out the scientific gap. After that, the overall concept picture from the view of a company is presented, and the focus of this work is outlined. Therefore, this chapter includes the fourth phase of applied research, where the concept of the relevant application context is introduced. Then, the chosen and created design model for the ICT solution is explained. Last, the requirements for calculation model selections are defined and compared to the existing calculation models to select a suitable model for validating the results of this dissertation.

**Chapter 5** outlines the following approach and detailed service description for the development concept and realization of the ICT solution. Besides the detailed service description, the chapter also consists of the results of the service execution tests, the description of the service deployment in a sample company, and the illustration of the service benefits. Therefore, on the one hand, the relevant application context is analyzed and shown; on the other hand, its working procedure is evaluated with the help of some execution tests.

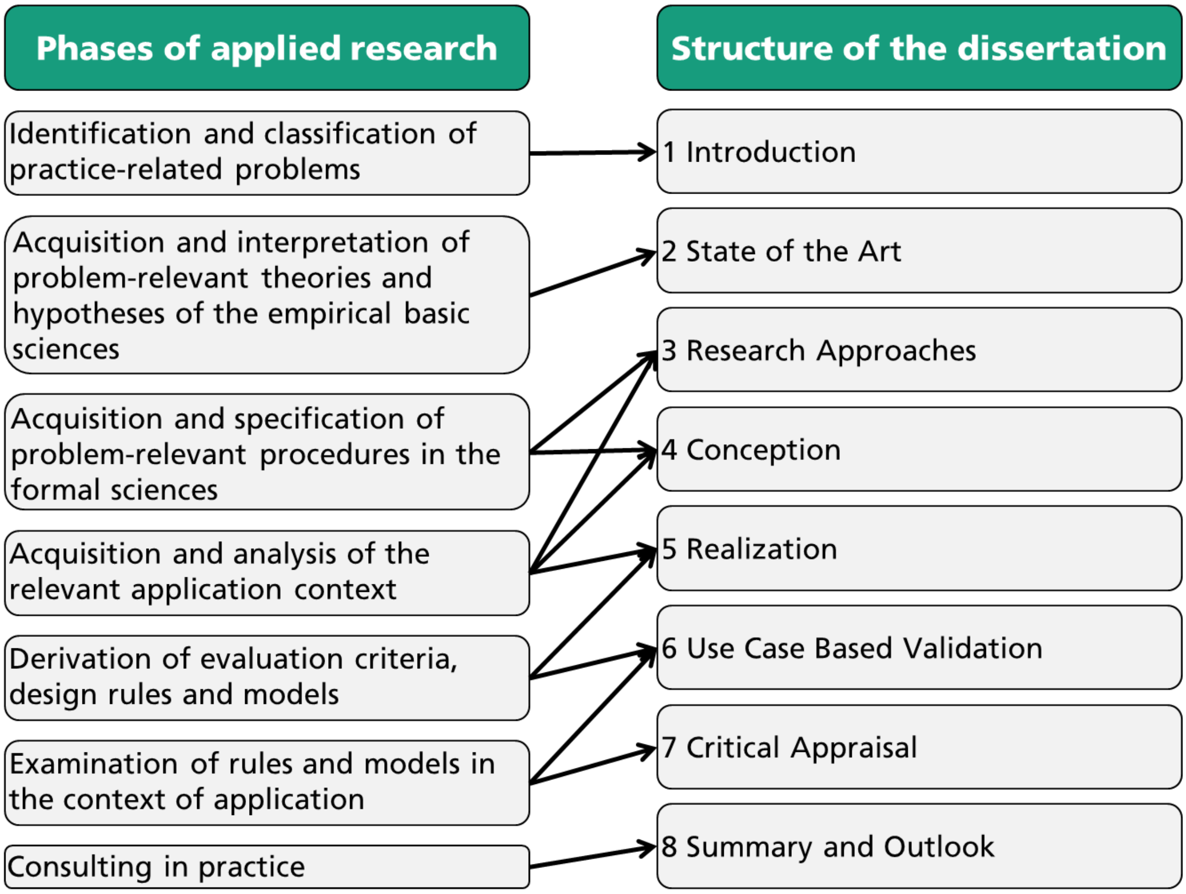



Figure 1.2: Structure of the dissertation aligned with (Ulrich et al. 2001, pp. 21–40)

The evaluation criteria (fifth phase of applied research) for the developed approach in this dissertation are derived, a validation method is performed in different use cases, and the validation results are presented to determine whether the ICT solution is financially feasible in **Chapter 6**. The critical appraisal of the author about the results of this work is indicated in **Chapter 7.** In this chapter, the fulfillment of the defined requirements for the ICT solution development is evaluated, and it is verified that all research questions are adequately answered with the results of this dissertation to realize the phase of applied research (examination of the rules and models in the context of application). **Chapter 8** summarizes the findings and gives an outlook on further research needs.

# 2 State of the Art

In the following, the definition of the battery is described. Next, the energy flexibility in manufacturing is defined and different AGV battery technologies, charging methods, and schemes are presented. Then the meanings of the DR and the peak shaving are described. Moreover, the definition of digitalization in manufacturing is explained. After explaining the terms battery and digitalization, the evolvement of the information technology (IT) system architectures is shown. Then, the RAMI 4.0 model is introduced, which is applied in the concept description. After that, the essential terms for the simulation and the following approach to design a simulation are described. Finally, the different validation methods to perform investment calculations are shown.

## 2.1 Battery (Accumulator)

A battery is a device that consists of one or more electrochemical cells with exterior poles (Crompton 2000, p. 1/9) for electrical power devices such as electric cars, AGVs, mobile phones, etc. The electric current (electrons) flows through a battery from its positive pole, the cathode, to its negative pole, which is called the anode (Pauling 2014, p. 539).

When a battery is connected to an external electrical load, a redox reaction transforms high-energy intercalants into a redox reaction toward lower-energy products after a battery is coupled to an electrical load. The transferred free energy difference to an electrical load is called electrical energy (Schmidt-Rohr 2018, p. 1801). According to (DIN 40729, p. 2), the term battery is defined as several connected cells.

The battery is the generic term for energy storage and a primary battery. Batteries that cannot be recharged are called primary batteries. Batteries that can be recharged are secondary batteries or, more commonly, accumulators (rechargeable batteries for short) (ZVEI 2021).

In the following, first, the different battery technologies are introduced. Then battery usage applications are shown. Last, two different types of battery degradation are explained.

The battery technologies that AGVs utilize are considered in following. According to Ullrich et al. (2019, p. 99), three battery technologies are relevant as an energy supply of AGVs. These are lead, nickel batteries, and lithium batteries. Below, the following three battery technologies are defined:

- **A lead accumulator** (lead battery for short) is an accumulator in which the electrodes are made of lead or lead dioxide, and the electrolyte is diluted sulfuric acid. Gaston Planté invented the lead battery in 1859 (Pavlov 2011, p. 4). Lead accumulators are considered reliable and inexpensive for a service life of several years. Compared with other accumulators, they have a large mass with a volume and a low energy density of 0.8-0.9 kWh/L (May et al. 2018, p. 156). The best-known application is the starter battery for motor vehicles. They are also used as energy storage for EVs. However, their use for this purpose is limited due to their large mass and temperature dependence (Pavlov 2011, p. 77).
- **Nickel batteries** can be sorted into two categories. One is the **nickel-cadmium (NiCd)** battery, which uses nickel oxide hydroxide and metallic cadmium as electrodes. The usage of NiCd is reduced because of the toxic metal cadmium during the disposing. According to European Commission (2020, p. 1), the use of NiCd batteries is restricted and can only be provided for substitution purposes. Therefore, it is not considered as battery technology in this work. Another one is the **nickel-metal hydride battery (NiMH)**. NiMH is an accumulator with a positive electrode made of nickel (II) hydroxide and a negative electrode consisting of a metal hydride. Stanford R. Ovshinsky and Masahiko Oshitani developed the technical principles. NiMH accumulators are widely used in standard battery designs and deliver a nominal voltage of 1.2 V per cell with a typical end-of-discharge voltage of 1.0 V. Compared to NiCd batteries, NiMH batteries offer approximately twice the energy density at the same voltage. In addition, they are more long-lasting compared to NiCd batteries, and the memory effect is almost eliminated due to the different processing (Linden et al. 2002, chapter 27-28).

- **Lithium** batteries consist of different technologies. This dissertation considers only the **lithium iron phosphate battery (LFP).** LFP battery is a version of a lithium-ion accumulator with a cell voltage of 3.2 V or 3.3 V. The positive electrode consists of LFP instead of conventional **lithium cobalt oxide (LCO)**. The negative electrode consists of graphite (hard carbon) with embedded lithium. Such an accumulator has a lower energy density compared to the conventional one but does not tend to have thermal runaway - even in case of mechanical damage (Rao 2014, p. 11). LFP batteries also do not suffer from the memory effect as, for example, NiCd batteries. LFP accumulators have significant advantages over lead-acid accumulators in cycle stability, size, capacity, and weight. The disadvantage is the higher purchase price of LFP accumulators compared to electrically equivalent solutions with lead-acid accumulators. In addition, there are balancers, which are not necessary with lead batteries (W. Communications Ltd 2005).

Batteries are used in various applications to supply energy to its user. This chapter describes three necessary usage modules of batteries, which can be used to reduce peak loads in industrial plants.

- **Stationary battery**: Individual battery cells are connected serially and parallel to a battery module and pack to build a stationary battery. On the one hand, serial wiring of battery cells enables the requested voltage level of battery modules or packs. On the other hand, parallel wiring of cells increases the usable battery capacity. Cell voltage leveling poses a challenge in serial battery cell wiring topologies, which a battery management system can solve. Stationary batteries are built on groups of one to several battery cells wired in parallel, then wired in serial to form a battery module. Multiple battery modules are wired together within serial-parallel configurations to reach the required stationary battery capacity (Hesse et al. 2017, p. 10).
- **EV battery:** EV batteries are built similarly to stationary batteries. An EV battery can be described as an electrochemical cell group that generates an electric potential at the battery circuits. This circuit is completed after an electrical load; for example, the motor is wired to an EV battery. Therefore, the current from the positive circuit of an

EV battery can flow through to an EV motor to generate the torque. Then this current flows back to the negative circuit of an EV battery to close up the circuit. So that the EV battery is discharged during this process. It is also possible to charge the EV battery if an external power source is used to reverse the current flow through the EV battery. The most used EV battery technologies are lead-acid, NiMH, and lithium-ion batteries (Dhameja 2002, p. 4).

- **AGV battery:** AGVs must be supplied with power for the vehicle control system, the electrics, electronics and sensors, the traction, steering drives, and the equipment for load suspension. Three standard battery technologies are used to power the AGV. They are lead-acid, NiCd, and lithium-ion batteries (Ullrich et al. 2019, p. 99). Here are some examples of cathode materials (LCO, Lithium Manganese Oxide Spinel, Lithium Nickel Cobalt Manganese, LFP, Lithium Nickel Cobalt Aluminum Oxide) and anode materials (graphite, lithium titanate oxide, silicon) are listed (Ullrich et al. 2019, p. 100). The detailed description and comparison of battery technologies for AGV are in chapter 2.6.

It is a challenging objective to identify the degradation and aging processes in a battery. This is because of different environmental or utilization mode factors that interact to induce other aging impacts. Consequently, decreasing capacity and resistance growth does not rely on the same resources, making aging a problematic challenge to understand (Barré et al. 2013, p. 681). According to Meissner et al. (2005, pp. 449–451), battery degradation can be classified into two main categories:

- Calendar aging
- Cycle aging

**Calendar aging** causes a non-reversible fraction of the decrease in capacity, which occurs when the battery is in storage (Sarre et al. 2004, pp. 66–67) (Erdinc et al. 2009, p. 384). The storage conditions determine the self-discharge rate of the battery capacity (Ritchie 2004, p. 287). According to the research of different studies, two primary conditions for calendar aging are identified. One condition is the storage temperature (Bögel et al. 1998, p. 41). At high temperatures, secondary reactions such as corrosion are favored, and lithium loss is more significant than at moderate temperatures, which leads to a decrease in capacity (Amine et al. 2001, pp. 685–686) (Bloom et al. 2001, p. 238) (Wright et al. 2002, p. 450). Low temperatures restrict the progression of these phenomena, but these conditions generate some issues by preventing material dissolution and changing the battery chemistry (Zhang et al. 2004, p. 1057). Another essential condition for calendar aging is the state of charge (SOC) level. The SOC indicates the number of ions present at the electrodes. Therefore, the higher the SOC level, the more increased battery aging occurs (Kassem et al. 2012, pp. 298–299) because a high level of SOC implies a significant potential imbalance at the electrode/electrolyte interface (Barré et al. 2013, p. 682).

On the other hand, **cycle aging** depends on the discharging and charging of a battery. Many factors, the type of usage, the temperature conditions, and the current load of the battery, are involved in this type of aging. Two critical variables impact the cycle aging. One is the SOC variation during a cycle; another is a battery's charging/discharging voltage level (Barré et al. 2013, p. 684). The battery cycles describe the battery’s health. After the battery cycles are processed, the battery capacity reduces to 80%, called depth of discharge (DOD) (Guena et al. 2006, pp. 3–4).

## 2.2 Energy Flexibility in Manufacturing

Towards the energy transformation in Germany, the number of photovoltaic (PV) and wind power plants integrated into the power grid is increasing (BMWi 2010b, p. 8). As a result of the energy transformation in Germany, manufacturing companies are challenged to sustain energy-cost-efficient manufacturing (Keller et al. 2016, p. 752). The traditional strategy – adjusting and managing the energy demand on the power generation side - is often used to solve this problem.

In addition to this solution, developing new strategies to make the energy demand of factories more flexible is a decisive task for manufacturing companies to enable production systems to cope with the varying character of renewable energies (Schulze et al. 2019b, p. 330). The flexible adaption of energy demand (energy flexibility) can be another strategy to balance the power grid.

According to different researchers, energy flexibility is defined as follows:

- Energy flexibility is the ability to quickly adapt to changes in the energy market at a meager cost (Reinhart et al. 2012, p. 623).
- Energy flexibility defines the ability of a production system to adapt itself to changes in the energy market (Graßl et al. 2014, p. 303).
- Energy flexibility can also be understood as the ability of a system to adapt its energy requirements to a target function (Graßl 2015, p. 27).
- "… the ability to adapt the manufacturing systems to short-term changes within the energy market with little loss in time, effort, costs, and performance." (Keller et al. 2016, p. 752)

In summary, energy flexibility in manufacturing can be defined with the help of the definitions above as an ability to manage and adapt the energy demand of manufacturing systems to changes and requirements of the energy market quickly and cost-effectively.

The mechanism to enable energy flexibility in the power grid is called DR, which is often assisted by IT. In the next chapter, first, the definition of DR is explained. Then the load-control method of *peak shaving* is introduced in detail, which is an essential motivation for the DR from the point of view of the manufacturing companies.

## 2.3 Demand Response and Peak Shaving in Manufacturing

Conventional power plants help control power generation to respond to changes in electricity consumption (Papaefthymiou et al. 2018, p. 1027). The amount of renewable energy implementation and their inherent volatility increase day to day, which causes that controlling power generation is not a good strategy anymore (BMWi 2010a, p. 7). Commonly, there are five existing options to increase the flexibility in the electricity grid:

- New flexibility on the supply side (Lacal Arantegui et al. 2018, p. 2470)
- The power grid expansion (Battaglini et al. 2012, p. 254)
- New storage capacity installation (Lund et al. 2016, p. 3)
- Conversion between sectors (Papaefthymiou et al. 2018, p. 1032)
- New flexibility on the demand side (Roesch et al. 2019, p. 1).

However, since the first four points show some disadvantages, DSM and especially DR are determined options that are gaining more interest lately.

DR is a section of DSM that can be defined as a modification to respond to the changes in the electricity grid that influence the level or timing of demand in the short term (Albadi et al. 2008, p. 1990) (Markle-Huss et al. 2016, p. 1010). (Jazayeri et al. 2005, p. 1504) defines the DR as load control, which consists of load connection, load disconnection, and load shift.

An essential motivation for companies to realize DR is peak shaving (VDI 5207-1, p. 26). Peak shaving enables power consumers to reduce peak loads by shifting them from peak to off-peak hours. Therefore, companies can reduce their electricity cost, resulting from transmission and distribution system charges (Uddin et al. 2018, p. 3327). However, today's electricity systems lack fully automated peak shaving applications (Uddin et al. 2018, p. 3329) (Roesch et al. 2019, p. 8).

The power price can be reduced by reducing peak loads in the load profile. For this purpose, load peaks are identified in the load profile, and the ESS is dimensioned based on these peaks (Zimmermann et al. 2019, p. 22). The following formula shows the calculation of the grid charge:

$$Grid\ charge = Power\ price\ x\ Annual\ maximum\ power\ (1)$$

This work focuses on the industrial grid's peak shaving application with AGV batteries. Therefore, the different research results about the peak shaving applications in manufacturing plants are presented in 3.1.

## 2.4 Digitalization in Manufacturing

This dissertation uses the benefits of digitalization in manufacturing. Therefore, this chapter focuses on the basic definition of digitalization in manufacturing. First, the terms manufacturing and factory are described. Second, digitalization and automation are explained. Then digital transformation is defined, and its development levels are introduced. Last, the technologies and enablers of digitalization in manufacturing are described.

Production is defined by the authors Westkämper et al. (2016, pp. 1–9) as a transformation process in that higher quality products are manufactured from natural assets in factories by using knowledge. The relationship between production and manufacturing is clarified by Warnecke (1995, p. 1) to mean that production consists of parts manufacturing and assembly.

To differentiate the term factory from production, the term factory is described in Schenk et al. (2014, pp. 1–6) as the place where industrial goods production is performed using factors of production and based on the division of labor.

Automation is realized by exchanging data between the production process and the automation facilities. Interlinking of numerically controlled production equipment can be implemented in automation with the help of information and communication technology (digitalization) (Heinrich et al. 2017, pp. 1–29).

According to Hippmann et al. (2019, p. 9), digitalization means “the binary representation of texts, [...] as well as properties of physical objects in the form of sequences of 1s and 0s [...] “.

Digitalization in production is regarded as a revolutionary approach to enhancing production speed and precision. Under the synonym "Industry 4.0", digitalization is considered the fourth industrial revolution after the invention of the steam engine, industrialization, and the beginning of the computer age (Bauer et al. 2018, pp. 180–181).

Digital transformation is defined by the German Federal Ministry for Economic Affairs and Energy as the intelligent interconnection between people, machines, and industrial processes (BMWi 2020). The authors Bauernhansl (2018, p. 2) outline the digital transformation in production in four levels (see Figure 2.1).

The first level is digitalization, in which the analog processes are represented digitally. The processes are digitally mapped in the second development level of digital transformation. Digital tools and technologies, industrial internet of things, cyber-physical systems (CPS), etc., are applied in the third level to connect the whole value chain. Autonomous systems are realized at the last development level by combining traditional technologies and artificial intelligence. The next chapter describes the technologies and enablers of digitalization in manufacturing.

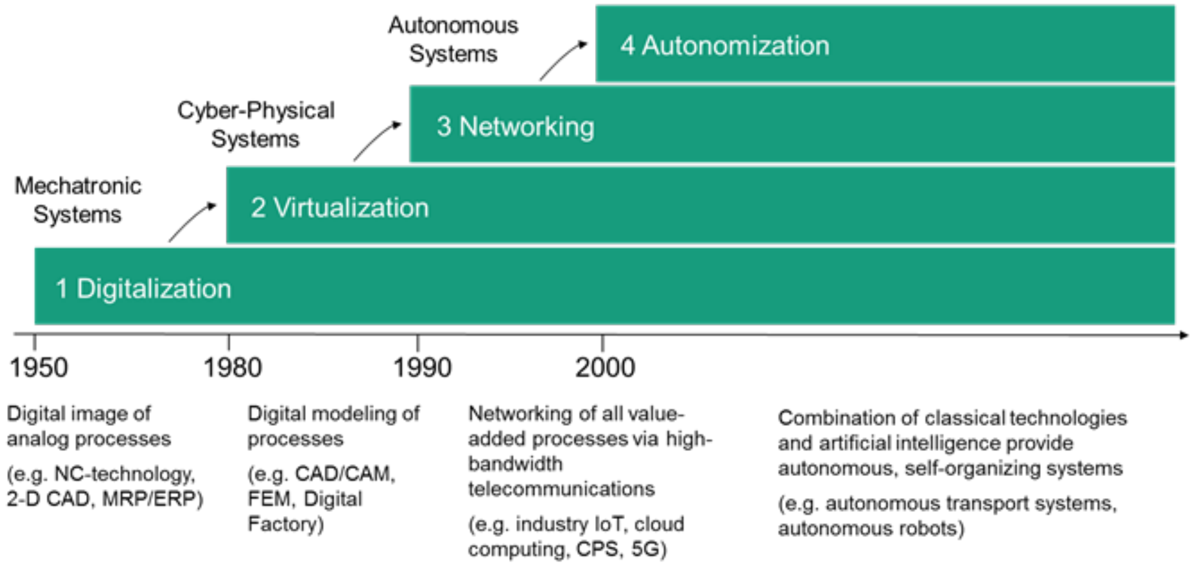



Figure 2.1: The digital transformation levels according to Bauernhansl (2018, p. 2)

The following digitalization technologies are relevant and applied in this dissertation. Therefore, definitions of these technical terms are introduced below in more detail.

**CPS** are items, devices, buildings, means of transportation, production facilities, logistics components, etc., that include embedded systems that are enabled to communicate. These systems can interact via the Internet and utilize Internet services. CPS can directly detect their physical surroundings with appropriate sensor equipment, evaluate and save them with the help of globally accessible data and services, and influence the physical environment with the assistance of actuators (Bauernhansl 2017, p. 12).

The CPSs can then connect and build networks autonomously and decentral - in line with these self-similar production fractals - and optimize themselves independently (Bauernhansl 2017, p. 12). An AGV can be given as a CPS example. AGVs consist of hardware and a software system that communicates with a central control system, which receives tasks from this control system and operates AGVs according to these tasks.

**Cloud computing** plays a decisive role in the networking of components. With the ability to be accessed via the Internet and the service-oriented nature of cloud services and their service-oriented nature, cloud services can be easily operated via interfaces and, in turn, access other services directly. These properties are also present in the ongoing development of Industry 4.0: Production plants and their components possess standardized interfaces, which enable uniform and straightforward control of equipment functions and information. An interface allows systems to be opened up and interoperability between different components. Equipment can also be reached by standardizing the interfaces (Fallenbeck et al. 2017, p. 139).

Cloud services are particularly suitable for networking distributed components in Industry 4.0. They allow the central storage of data, its evaluation, and finally, access to the distributed features, for example, to import software updates or make configuration changes. Cloud infrastructures comprise physically distributed systems for storing and processing data managed by a cloud management component (Fallenbeck et al. 2017, p. 144). The Energy Synchronization Platform (ESP) (Bauernhansl et al. 2019, p. 250) can be given as an example of a cloud computing framework.

**Robotics** offers excellent usage cases for Industry 4.0 technologies due to the universal usability and the demand to configure the robot and its auxiliary equipment for a specific manufacturing job. Robotics is often applied to help transform materials in an automated way on the shop floor (Naumann et al. 2017, p. 201). These are called material handling systems, which work either steadily or as needed. There are various existing technologies such as “[…] belt, roller, and vertical conveyors, elevators, material handling robots and automated guided vehicles (AGVs) […]" to conduct the transfer of materials (Martinez-Barbera et al. 2010, p. 459). CPS is termed as a system regarding Industry 4.0, which combines human cognition, physical sensors, and actuators. AGVs are an example of such intricate manufacturing elements (Bubeck et al. 2017, p. 83). AGVs are an essential part of this work and will be described in more detail in the following chapters.

## 2.5 Evolvement of IT System Architectures

An algorithm-based ICT solution is developed as a software service (IT system) in this work. Therefore, it is essential to comprehend the evolution of IT system architectures and describe their historical development. First, the concept of the automation pyramid according to the International Standards of Automation (ISA) 95 model is shown. Then the steps leading to the Industry 4.0 service-oriented architecture (SOA) vision are presented.

Previous approaches to network parts of production IT using Computer Integrated Manufacturing (CIM) were already launched in the 1980s. However, this failed because of the complexity, customization of a few suppliers by using their in-house proprietary interface, and the early stage of the technology. Nevertheless, the automation pyramid was developed parallel based on the CIM pyramid developed in the 1970s and 1980s (Siepmann et al. 2016, pp. 17–82). It details how business process-relevant IT systems are integrated with IT systems for controlling production technology and has been mainly applied by large companies in their production (Bildstein et al. 2014, p. 582). Many variants of this pyramid have progressed through the years. One of them is shown in Figure 2.2 and characterized by Siepmann et al. (2016, pp. 17–82) based on (ISA 2000, p. 16).

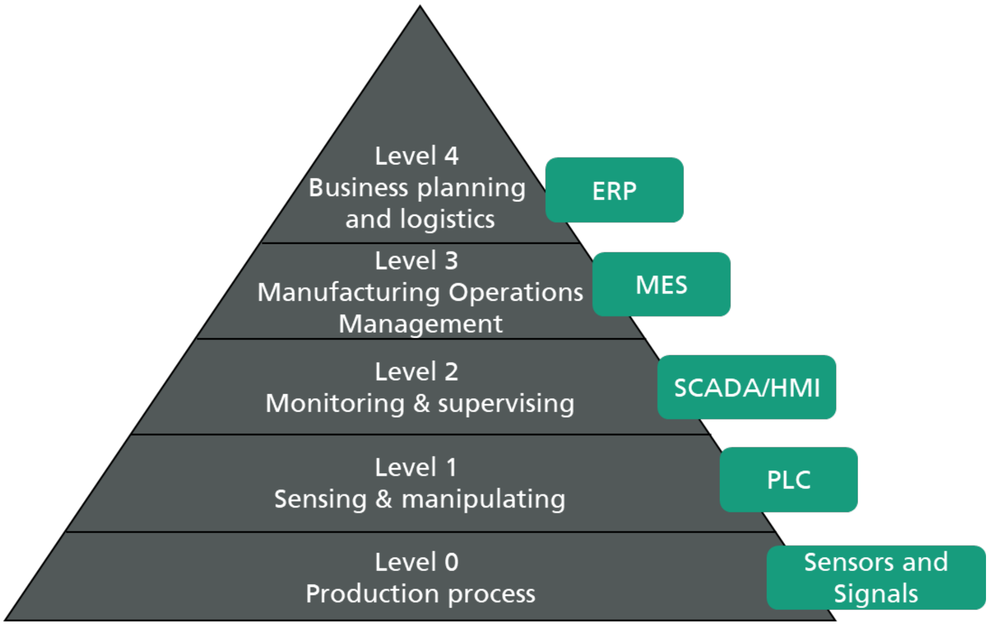



Figure 2.2: The automation pyramid based on ISA 95

Level 0 describes the production process and includes sensors and signals on the shop floor, collecting process data on the upper levels. In level 1, the production systems, such as machines, can be sensed and manipulated with the help of the programmable logic controller. The next level has the tasks of monitoring and supervising production. The machines are monitored with a human-machine interface (HMI) and supervised by supervisory control and data acquisition. In level 3, a manufacturing execution system (MES) is used to create, track production orders and plan shifts for machines and production workers. MES controls all manufacturing operations. The upper level manages the core business processes, such as sales, customer services, human resources, etc., with the help of an enterprise resourcing planning software tool.

The SOA prevails over decentralized decision-making, which is a crucial characteristic of Industry 4.0 (Saldivar et al. 2015, p. 5) (Mittal et al. 2019, pp. 1354–1355). To realize this, the traditional automation pyramid should be adjusted so that any system can communicate to another system module decentral. Figure 2.3 indicates the Industry 4.0 vision. Industry 4.0 aims to establish modules that are managed locally without a hierarchy.

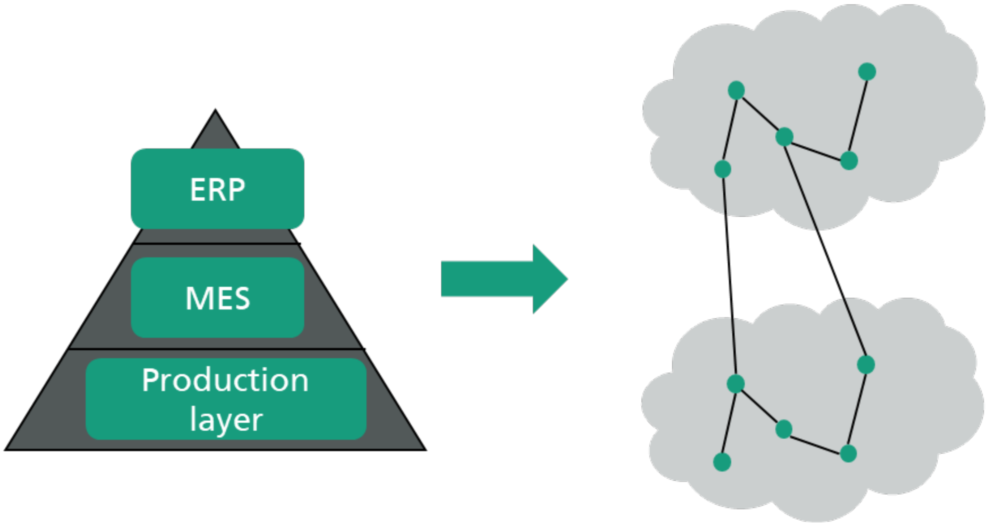



Figure 2.3: Steps leading to the Industry 4.0 vision

With the SOA, locally managed software modules can be created, which is called a microservice architecture in the industry. So-called micro services generate a fine-grained application instance structure in this architecture (Götz et al. 2018, p. 168).

The ICT solution developed in this dissertation also operates as a microservice and is a part of the SOA.

## 2.6 Automated Guided Vehicles

In the following, first different AGV battery technologies are presented. Second, the different AGV charging methods and schemes are introduced according to the state of the art. Last, the AGV control system software is shown.

"Automated guided vehicle systems (AGVS) are in-house, floor-supported materials handling systems comprising automatically controlled vehicles whose primary task is materials transport rather than the transport of passengers" (VDI 2510, p. 7).

Among the most critical flexibility factors for conveyor technology is the ability to adapt to the existing production environment, transport a broad range of goods, react to productivity fluctuations, and modify the handling sequence.

AGVS offers the highest degree of flexibility of all automated conveyor systems. Minimum infrastructure requirements, the use of existing routes, and the option of easy replacement by another vehicle or a conventional forklift truck can be counted as further advantages of AGVS (Ullrich et al. 2019, p. 180).

Table 2.1 shows the characteristics of common battery types used in mobile energy storage devices. Since there are different structures for most battery types, the given values sometimes match differently. According to Crastan (2018, pp. 499–520) Friedrich (2016, pp. 27–60), they are as follows:

Table 2.1: Comparison of battery technologies

| | Lead | Nickel- | | Lithium - | |
|---|---|---|---|---|---|
| | | cadmium | metal hydride | Ion | iron phosphate |
| **Cathode material** | $PbO_2$ | NiO(OH) | NiO(OH) | $LiCoO_2$ | $LiFePO_4$ |
| **Anode material** | Pb | Cd | MH | graphite | graphite |
| **Electrolyte** | $H_2SO_4$ | KOH | KOH | $LiPF_6$ | n.a. |
| **Nominal voltage** | 2.0 V | 1.2 V | 1.2 V | 3.6 V | 3.3 V |
| **Cut-off voltage** | 1.7 V | 1.0 V | 1.0 V | 3.0 V | 2.0 V |
| **Operating temperature** | -20 to 60°C | -40 to 60°C | -20 to 60°C | -20 to 60°C | -20 to 60°C |
| **Energy density** | 40 Wh/kg | 45-60 Wh/kg | 80 Wh/kg | 120-200 Wh/kg | 90-110 Wh/kg |
| **C-rate / performance** | very high | very high | high | low | very high |
| **Self-discharge per month** | ~5 % | ~ 20 % | ~30 % | 5 % | 5 % |
| **Cycle life** | 200-300 | 1000-1500 | 300-500 | 500-1000 | 2000 |
| **Charging voltage** | 2.3-2.6 V | C/10 | C/4 | 4.2 V | 4.0 V |
| **Charging duration** | 20 h | 11 h | 5 h | 3 h | 1.5 h |
| **Charging efficiency** | 70-80 % | 70-90 % | | 70-96 % | |

According to Ullrich et al. (2019, p. 99), three AGV battery charging methods are addressed in this work and described below.

- **Charging traction batteries:**

The AGV is charged at a charging station (plug-in conductive charging) or on charging rails by connecting to an energy source. There must be sufficient time to recharge the energy taken at the charging location. The batteries remain in the vehicle for the entire day and are only charged by intermediate charging (Ullrich et al. 2019, p. 102).

- **Non-contacting energy transfer (inductive charging):**

Electrical energy is transferred inductively to an AGV without permanently contacting a conductor laid in the ground with contactless power transmission. Supplying the AGV with power is suitable for simple AGV layouts such as those used in car series assembly. This isn't easy for complex layouts in which the AGV is used in taxi operations (Ullrich et al. 2019, p. 104).

- **Hybrid system:**

A hybrid power supply system for AGVs consists of contactless power transmission and a supporting battery or double-layer capacitors. The capacity of a supporting battery is smaller than the traction batteries mentioned above and fulfills only limited tasks. In case of a malfunction, the vehicle can be removed from the layout with the help of the backup battery in order not to disturb the other AGV. The backup battery also helps the AGV to reach the next inductive charging point in this system (Ullrich et al. 2019, pp. 106–107).

In this work, five AGV battery charging schemes, according to McHaney (1995, p. 3026), are considered and described below.

- **Manual battery swapping:**

The discharged AGV battery is swapped manually with a full battery when the battery level of an AGV is below a defined SOC value. The discharged battery is then charged outside an AGV at the charging station (McHaney 1995, p. 3026).

- **Automatic battery swapping:**

The discharged AGV battery is swapped automatically with a full battery through an automatic swapping system, which takes less time to swap the battery than manual battery swapping. The discharged battery is then charged outside an AGV at the charging station (McHaney 1995, p. 3026).

- **Opportunity charging:**

AGV battery is charged on every possible occasion (e.g., breaks, lunch, and shift changes) in the opportunity-charging scheme. It is used when AGVs have many short and predictable stops. The AGV batteries are charged at the charging stations when AGVs are stopped. This charging scheme is used most often in assembly operations. While the assembly operations occur, the AGV battery is only charged to have enough SOC to move to the next working station in its scheduling (McHaney 1995, p. 3026).

- **Automatic charging:**

AGV works until its battery has depleted to a certain SOC level in this scheme. Then, the AGV will be scheduled to go to a charging station, and its battery will be charged until the SOC level of the AGV battery receives an acceptable level. As described in the opportunity charging, the AGV batteries are also charged at the charging stations until an adequate SOC level is reached (McHaney 1995, p. 3026).

- **Combination charging:**

Combination charging is a mix of opportunity and automatic charging. First, the AGV battery is charged according to the opportunity-charging schema. Once the SOC of an AGV battery has decreased to a specific lower level, the AGV will be scheduled to go to a charging station and waits until the SOC of the AGV battery reaches an acceptable level (McHaney 1995, p. 3026).

The ICT solution developed in this dissertation will be a part of an AGV control system. For this reason, the term AGV control system will be described in this chapter.

(VDI 2510, p. 7) defines an AGV control system as follows: An AGV control system consists of hardware and software. The core is a computer program that runs on one or more computers.

It coordinates several AGVs and integrates the AGVs into the in-house processes. According to Ullrich et al. (2019, p. 60), the AGV control system has four tasks:

- Integrating the AGV into its environment
- Accepting transport orders
- Offering the operators several service options
- Providing function blocks corresponding to the tasks

The AGV of the third epoch is a hierarchical system. This means that the individual AGVs operate intelligently but not autonomously. The AGVs communicate with each other rarely or never and make hardly any decisions of their own. The actual decision-making authority lies with the higher-level AGV control system. This grants it overall responsibility and the rules necessary to manage the AGV system (Ullrich et al. 2019, p. 60).

In the next chapter, the reference architectural model industry 4.0 (RAMI 4.0), used as a model in this dissertation to create the concept of this work, is introduced.

## 2.7 Reference Architectural Model Industry 4.0

RAMI 4.0 is a three-dimensional layer model that compares the life cycle of products, factories, or machines with the hierarchical levels of I4.0 (Heidel et al. 2017, p. 41). The model divides the existing norms and standards into manageable and small parts. The aim is to structure the interdisciplinary subject area of I4.0. RAMI 4.0 is divided into three axes (Heidel et al. 2017, p. 41). These axes are

- Life Cycle & Value Stream
- Hierarchy levels
- Layers.

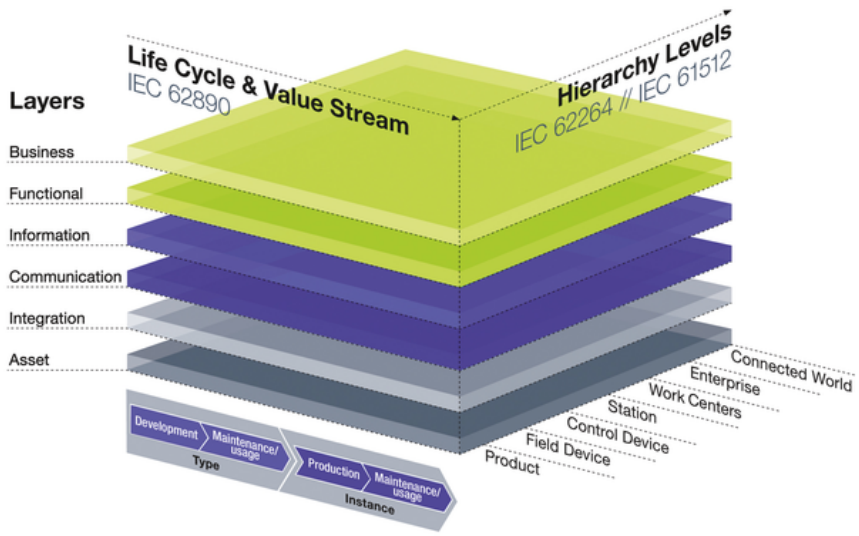



Figure 2.4: RAMI 4.0 Model according to Heidel et al. (2017, p. 41)

Figure 2.4 indicates the RAMI 4.0 model according to Heidel et al. (2017, p. 41). The life cycle and value stream axis describe the initial idea of an asset to its disposal and are divided into four phases (Heidel et al. 2017, p. 43):

- Development (Type)
- Maintenance /Usage (Type)
- Production (Instance)
- Maintenance/Usage (Instance).

The hierarchy levels axis is used for vertical integration, e.g., within a machine or factory. IEC 62264, IEC 61512, ISA88, and ISA 95 organize hierarchies within plants and factories. The hierarchy axis is divided into seven levels (Heidel et al. 2017, p. 44):

- Product
- Field Device
- Control Device
- Station

- Work centers
- Enterprise
- Connected World.

With the help of the layers axis, systems in the information world are planned and implemented, taking into account the physical world. The layers axis comprises six categories (Heidel et al. 2017, p. 45). These are

- Business (information world)
- Functional (information world)
- Information (information world)
- Communication (information world)
- Integration (information/physical world)
- Asset (physical world).

A generally valid data model is introduced in this work with the help of RAMI 4.0. It allows using the advantages of I4.0, such as connectivity between all devices. Therefore, RAMI 4.0 is used to design a concept for enabling energy flexibility in manufacturing with company AGV lithium batteries through an algorithm-based ICT solution. A detailed description of the axes and their levels of RAMI 4.0 is introduced in chapter 4.3.3 with the developed generic concept of this work.

## 2.8 Simulation Modeling

This chapter introduces the definition of simulation, a recommended approach to generate a simulation, and simulation modeling methods.

A simulation represents a physical system and its related processes in a model. Its goal is to obtain transferable results for practical applications (VDI 3633, p. 3). The terms system and model are related to the term simulation. The system is a collection of components and properties connected by interdependencies (Hall et al. 1956, p. 18). A model is an abstract image of a system (Eley 2012, p. 3).

If computers are used for the necessary calculations in the simulation, this is called a computer simulation. For this purpose, the model must be available in a mathematical-logical form and implemented in a computer program. These computer programs are considered simulation tools (Eley 2012, p. 4).

A simulation run or experiment is the reproduction of the behavior of a system with a model over a certain period of time (VDI 3633, p. 3). This specific time period is called simulation time. On the other hand, the simulation time represents the time progressing in the real system in the simulation model (Eley 2012, p. 4).

According to (VDI 3633, p. 18), the following approach is recommended to create a simulation:

1. Formulation of problems
2. Test of simulation-worthiness
3. Formulation of targets
4. Data collection and data analysis
5. Modeling
6. Execution of simulation runs
7. Result analysis and
8. Documentation

This approach above is used to create three simulation models in this work. The built simulation models within the scope of this work are described in more detail in chapter 6.1. Different modeling methods can be used to solve various problems according to the simulation project goals, the accessible data, and the type of system to be modeled. According to Borshchev (2014, p. 248), these methods are

Discrete event (DE): DE paradigm “adopts a process-oriented approach: the dynamics of the system are represented as a sequence of operations performed over entities” (Borshchev 2014, p. 248).

Agent-based (AB): AB model “describes the system from the point of view of individual objects that may interact with each other and with the environment” (Borshchev 2014, p. 248).

System dynamics (SD): SD modeling “suggests abstracting away from individual objects, thinking in terms of aggregates (stocks, flows) and feedback loops” (Borshchev 2014, p. 248).

## 2.9 Investment Calculation Models

The investment calculation uses a model based on economic data to determine a generally quantitative result that can be used as a basis for decision-makers when investing (Poggensee 2008, p. 9). Business management literature has established the payment-based and asset-based interpretations of the investment concept (Götze 2014, p. 5). While a cash flow characterizes payment-based investments, a company’s assets and capital are the starting point for an asset-based investment. With the help of investment calculations, it is possible to record and evaluate the quantitative aspects of an investment or an investment project and evaluate them. Therefore, they are an instrument for planning and controlling a rational investment decision based on an investment's economic advantageousness (Thommen et al. 2020, p. 384). In the following, based on a literature review using the works of Götze (2014) and Poggensee (2008), the models of investment calculation are described below.

The **cost comparison calculation** determines the costs of two or more investment projects and compares them. In principle, only those costs are included in the cost comparison calculation caused by the respective investment project. However, those costs incurred in the same amount for all investment variants are neglected (Thommen et al. 2020, p. 384). The assessment based on costs does not serve any purpose if the revenues generated by an investment differ from those generated by the omission alternative (Kern 1974, p. 121). This is the case since the omission alternative is the omission of the energy optimization service, and here no proceeds develop. In addition, the cost comparison calculation is only suitable for simple investment decisions. Since the case involves more factors than costs, a cost comparison calculation would not be sufficiently informative for an investment decision. The output of the model is the average cost. In contrast to comparative costing, revenues are also compared to costs. The profit, i.e., the difference between costs and revenues, are compared (Poggensee 2008, p. 66) (Götze 2014, p. 65) in **profit comparison calculation**. Profit comparison calculation compares the profits for given revenues of varying investment objects. If the investment projects require different capital inputs, it makes sense to include the rates of return in the assessment. Based on the cost and profit comparison calculation, the **profitability calculation** relates the average annual profit achieved to the average invested capital. With the help of the profitability calculation, several investment opportunities and individual projects can be evaluated (Thommen et al. 2020, p. 388). This model does not differ from the profit comparison calculation in the use cases; only a different target variable (profitability) is used. In the profitability calculation (also profitability comparison calculation), the ratio of a success variable (e.g., the profit) to a capital input variable, the so-called profitability, is calculated. The **static amortization calculation** - also referred to as the payback or pay-off method - determines the period of time that elapses until the payment surpluses repay the investment amount. Surplus cash inflows result from cash inflows with fewer outflows per period, calculated for simplicity's sake from the variables used in the income and cost comparison statements, assuming an even distribution over the period (Thommen et al. 2020, p. 388). The payback period, i.e., the period in which the investment costs of the energy optimization service can be recovered, can be calculated. However, since the duration of the service is very extensive, the result would not influence the investment decision. In static models, only one time period is explicitly considered (Götze 2014, p. 56). Since the given use case extends over several periods, dynamic models, which consider several periods, have an advantage. Total return on average investment capital determined by amortization or recovery period. In the **net present value (NPV) method**, all cash inflows and outflows caused by an investment are discounted to a specific point in time. The difference between discounted cash inflows and outflows is the NPV of an investment. The NPV corresponds to the asset change when the investment is conducted (Thommen et al. 2020, p. 392). In case there is enough data to make good predictions regarding service life, liquidation proceeds at the end of the service life, and calculation interest rate and the assumptions of the NPV model are observed, a comparison of NPV s for the energy optimization service can represent a valuable tool to support the investment decision.

Asset appreciation value is calculated according to the **horizon value method** at the end of the investment's service life (Poggensee 2008, pp. 139–140). Unlike the NPV method, the horizon value cannot be calculated for an infinite time period. The result of asset growth after a specific useful life also has no advantage compared to the more common capital value method, so the horizon value method should not be considered. The output of this model is the value of asset appreciation at the end of the service lifetime of the investment. The **annuity method** is a modification of the NPV method. In the NPV method, the NPV reflects the cash inflows and outflows over all periods of the investment period. However, the annuity method converts this NPV into equal annual cash inflows (Thommen et al. 2020, pp. 393–394). The same model is assumed for the NPV. The annuity method leads to the same result when analyzing the absolute advantageousness of an investment.

The **internal rate of return (IRR) method** can be easily derived from the NPV method. The internal interest rate, or IRR, results in zero NPV. The IRR corresponds to the capital investment rate or capital borrowing rate (Thommen et al. 2020, p. 394). The same model is assumed for the NPV. In contrast to the NPV analysis, however, the IRR method should not calculate the absolute benefit, as the premises (reinvestment premise, compensation for capital commitment, and valuable life differences) do not allow this. The period in which the investment is recovered from the deposit surplus is calculated in a **dynamic amortization calculation** (Götze 2014, p. 114). The same conditions and selection justifications of static amortization calculation also apply to this model. A **final asset value method** calculates an increase in financial assets resulting from the investment object in the last period (Götze 2014, p. 117). The output does not help answer the present question since the increase in financial assets in the last period is not crucial for the energy optimization service. The model’s output is an increase in financial assets caused by the investment object in the previous period.

A **debit interest rate method** calculates the interest rate at which the final asset value becomes zero. The method assumes a debit and credit interest rate (Götze 2014, p. 123). See the IRR method and final asset value method, the output of this model is a critical debit interest rate at which the absolute asset value becomes zero. It assumes debit and credit interest rates. Information on financial resources intake, investment, final asset value, intermediate values, withdrawals, and profitability is filled in tables with economic indicators over all periods in a **method of complete financial plans** (Götze 2014, pp. 126–127). Data such as repayment types, interest rates, etc., cannot be determined in the use cases. The output of this model is information on borrowing, investing, and offsetting differences in capital commitment. First, target criteria are determined and weighted in a **cost-benefit analysis**. Subsequently, partial benefits are determined, and then the total benefit values. Partial benefit values result in a total benefit when criteria are included. Later, the absolute advantageousness is determined via the determined benefit values (Poggensee 2008, p. 218). The cost-benefit analysis is particularly suitable for problems with several objectives. The output of this model is partial benefit values that result in an overall benefit when criteria are included. All investment objects are sorted in a **dean model** by descending return, and all financing options are sorted by ascending interest rates. Finally, they are presented in a diagram (Poggensee 2008, p. 229). As a representative of investment program planning, the Dean model benefits a cohort of several possible investments and financings.

The service life of an investment, i.e., the period between the beginning and the end of its utilization, is determined in the **models for service life, replacement time, and investment time decisions** (Götze 2014, pp. 251–252). This model group determines the service lifetime length, i.e., the period between the beginning and the end of utilization. The output of this model group is optimal service lifetime. The (simultaneous) optimal investment program is created in the **models for program decisions in security** (Götze 2014, pp. 309–310). See Dean-model; the output of this model is a (simultaneous) optimal investment program. The **sensitivity analysis** systematically determines the "sensitivity" of the investment results to changes in the input data such as sales volume, capital investment, calculation interest rate, or service life (Thommen et al. 2020, p. 396). In sensitivity analysis, the objectives, input factors, and distribution functions for these input factors are first determined. Then a method and an input example are selected. The result is validated, and, if necessary, an iteration of the model is performed (Götze 2014, p. 388) (Poggensee 2008, p. 305). Since sensitivity analysis can be applied in many ways to individual decisions and can show the reaction of output variables to a changed input. The outputs of this model are correlations between variable inputs and their advantages over other alternatives.

In a **risk analysis**, a decision model is created using probability distributions. Stochastic dependencies of input variables are included. Subsequently, a probability calculation is performed, and the results are interpreted (Götze 2014, p. 400). The output does not help to answer the question at hand since, instead of cost-saving, probabilities for the occurrence of different scenarios are determined. The results of this model are probabilities for the event of the target values. A **decision tree** of all decision possibilities in investment is created. The decision tree contains decision to chance, outcome nodes, and edges connecting these nodes. Once the decision tree is created, one can "walk along" the individual paths to calculate the probability of a specific decision (Götze 2014, p. 407). See risk analysis; the outputs of this model are non-directional graphs of all possible decisions, including probabilities. **Option pricing theory approaches** determine different operations and investment options (Götze 2014, pp. 420–421). Option pricing approaches can only be applied to economic investments of goods. The outputs of this model are different real-time operations and options. All efficient portfolios are formed from investment alternatives in a **portfolio-selection method**. A portfolio is efficient if none has a higher expected return for a given risk. The risk-utility function of the decision-maker is then determined, and the optimal portfolio is selected based on this (Götze 2014, p. 456). The output of this model is a risk measure for the financial investments in a portfolio. One possible way of implementing a **flexible planning method** is to create a state tree similar to a decision tree (decision tree method). Different environmental states and their incl. probabilities of occurrence and subsequent decisions are defined (Götze 2014, p. 464). See risk analysis and decision tree induction; the outputs of this model are different environmental states and their incl. probabilities of occurrence and consequential decisions.

# 3 Research Approaches

This chapter first indicates the applied research and industrial solution approaches (applications) in peak shaving with three battery technologies. Then, the existing AGV simulation concepts in production are presented. These concepts are later used to create a production line simulation with AGVs to generate realistic data, which are used to validate the developed service in this dissertation.

## 3.1 Peak Shaving Applications with Battery Technologies

It is common for manufacturing companies to have special electricity tariff models that contain the electricity price and the basic, working, and reactive power prices. Typically, it is a high cost of electrical energy for manufacturing companies and is based on the highest production load. Various battery usage applications and concepts have been developed to enable peak shaving in manufacturing operations. In the following chapters, the works of the researchers, which investigated the peak shaving opportunities with stationary, EV batteries in the industrial grid and AGV batteries, are introduced.

### 3.1.1 Applications with Stationary Batteries

This chapter illustrates the existing research on peak shaving applications with stationary batteries.

Böttiger et al. (2018, p. 102) simulated a lithium stationary battery model for peak shaving to lower operating costs and improve system lifetime in a manufacturing company. This paper pursues to determine the optimal system topology with the type and power rating of power electronic systems such as converters and switches. The paper’s findings show that the proposed model reduces operating costs and optimizes the system's lifetime. It also points out that different power electronics have little effect on economic costs.

Braeuer et al. (2019, p. 1424) determined the economic potential for installing battery storage systems (BSS) for German small and medium-sized companies and analyzed different BSS whose capacity is most suitable for the revenue stream -peak shaving-. A model with a linear program is developed to establish the optimal size of the BSS. The paper's findings show that none of the in the paper presented revenue streams, such as peak shaving, provision of primary control reserve, and energy-arbitrage-trading through intraday and day-ahead markets, individually economically attractive, but combined, they can be profitable for some companies.

Höne et al. (2019, p. 359) presented a techno-economic analysis for BSS in demand response applications such as peak shaving in manufacturing. Simulation modeling is used to perform a parameter study with the help of the different energy market scenarios. The paper's findings indicate that any economically viable investment scenario is achieved with 78 combinations considered in the simulation experiment.

A simulation tool Lehmann et al. (2016, p. 313) is developed to determine the optimal size of the PV and BSS during industrial peak loads for individual load profiles. The paper focuses on PV-BSS systems for industrial peak shaving applications. NPV is calculated with a method to evaluate the costs over the systems' service life. It is determined that NPVs are positive for system configurations with large PV systems compared to storage capacity.

Lu et al. (2018, p. 2) implements a new optimal load dispatch model for the industrial manufacturing process with the ESS. The paper results show that the energy costs can be reduced further by managing the ESS, while ESS is discharged during peak times and charged during off-peak times.

Oudalov et al. (2007, p. 621) developed an optimal operating strategy and designed a model for BSS to reduce peak loads. The model detects the BSS's optimal capacity and power to allocate the peak load shaving in the industrial grid. A dynamic programming application is developed to establish the optimal charging and discharging strategy for the BSS.

Schulze et al. (2019a, p. 683) presents that the energy demand of the production machines and processes can be flexibly adapted to current electricity generation and independent from electricity suppliers. The developed DSM scenarios show that the BSS can cover generation peaks by increased demands. The paper results show that the combination of the DSM and BSS is promising to conclude a high level of energy self-sufficiency in manufacturing systems.

Telaretti et al. (2016, p. 135) analyzed and compared the BSS with different battery technologies to find the most suitable battery technology for reducing peak load and electric bills of Italy's commercial and industrial consumers. According to the findings of this paper, lithium battery technology is most effective for peak shaving applications compared to other battery technologies.

Tiemann et al. (2020, p. 112539) analyzed more than 5,300 company sites to determine the profitability of the different BSS to reduce industrial grid fees. The researchers of this paper find out that the lithium-ion energy storages are most cost-effective in most use cases, compared to lead-acid and redox flow batteries; electricity costs for the usage of a grid and the investment costs for energy storage are related to the profitability of peak shaving.

Werle et al. (2019, p. 482) analyzed the aggregation effect on the battery sizing in an industrial production site. The batteries are used to reduce peak loads. They developed a machine-learning model that corrects the error of the non-optimal decisions for the battery aggregation, e.g., chosen battery capacity is insufficient for reducing peak loads. The paper results indicate that the developed models can sometimes correct this error.

To realize peak shaving in a Greek industrial facility, Zafirakis et al. (2014, p. 178) developed an algorithm that simulates different BSS usage strategies. This paper shows that it is not cost-effective to invest the energy storage to enable peak shaving in Greece. However, the researchers mentioned that the different industrial consumers have other peak loads, and it is essential to validate these use cases.

Zimmermann et al. (2020, p. 666) developed a methodology to determine which sizing of the BSS is optimal for different industrial peak shaving applications. According to the findings of this paper, lithium battery technology is one of the battery technologies which is cost-effective to be used in the peak shaving application.

### 3.1.2 Applications with EV Batteries

Besides stationary batteries, EV battery applications are also applied to enable peak shaving in industrial grids.

Amamra et al. (2019, p. 1) presented an optimal day-ahead scheduling strategy for EVs to reduce peak loads in an industrial grid by using the V2G system. Different simulations are developed to show the benefits of the proposed technique. The results indicate that the energy costs were reduced by using EVs during peak loads to cover them.

Hofmann et al. (2015, p. 4) has used the short-distance traveling employees' EVs to reduce the industrial grid's peak loads. A bidirectional charging concept is applied, and an algorithm for this concept is developed in this paper. According to the paper’s findings, the power efficiency measurements illustrate the comparable results promising improvements.

Raab et al. (2017, p. 1) developed a load balancing system, which uses EVs with the help of the V2G system to reduce industrial peak loads. This paper applies a stable operation and adequate response time to influence the load profile. This paper indicates that peak shaving is achieved using the load balancing system, and the proposed overall system is efficient.

### 3.1.3 Applications with AGV Batteries

The applications of AGV batteries in different areas, such as port terminals and production, are addressed in the presented papers.

Bohács et al. (2021, p. 294) developed a simulation model to integrate scheduling and energy efficiency aspects in production logistics using AGV systems. The results showed that the proposed method worked for priority production tasks and workload change. However, peak shaving is not considered in this paper. European Commission (2019) used AGV batteries in the Hamburg port to realize peak shaving in the electricity grid. However, the industrial grid is not considered in this application. Harnischmacher et al. (2021, p. 205) introduced a smart grid application to provide capacities for the energy grid of a container terminal by using transport vehicles’ batteries in less busy times. Ihle et al. (2014, p. 1) proposed an IT architecture to predict power demand at a container terminal and optimize this demand by modifying the battery charging schedules of AGVs. Optimizing the AGVs’ battery charging schedule is a significant part of this paper.

Yesilyurt et al. (2021, p. 1) investigated the benefits and potential of using AGVs as energy storage to reduce peak loads in manufacturing plants. An approximate cost calculation for peak shaving of a manufacturing company is applied in a use case scenario. The approximate cost calculation results indicate that the AGV batteries' usage to enable peak shaving in manufacturing plants can be beneficial for companies.

The different battery usage applications and concepts are developed to reduce peak loads with stationary, EV, and AGV batteries. However, reducing peak loads in an industrial grid with AGV batteries has yet to be the focus of the research.

## 3.2 Existing AGV Simulation Concepts in Production

The existing AGV simulation concepts in the production of four different papers are introduced in this chapter.

Ndiaye et al. (2016, p. 2595) introduces an AGV transportation system defined by a layout, several vehicles, several parking spaces, and a vehicle management policy. A simple formula is first used to determine the minimum required number of vehicles. Then, a discrete-event simulation model is used to evaluate different layouts and vehicle-dispatching policies. Initially, eight vehicles were required to meet the transportation demand, but with some optimizations, this number could be reduced to 4. While these optimizations reduce the number of vehicles, they incur additional costs during the implementation phase. This means that costs saved by reducing the number of vehicles are lost during the implementation phase in terms of software. In this paper Zhan et al. (2019, p. 558), two two-stage battery charging strategies are proposed for AGVs equipped with lithium-ion batteries to improve utilization. In stage 1, two routing decisions are developed, the nearest charging station (NCS) and the charging station with minimum delay (MDCS); in stage 2, reducing the duration of each charging operation considering the charging characteristics of the lithium-ion battery. A real case is adopted to illustrate the applicability and effectiveness of the proposed approach. These methods help improve manufacturing at short-term capacity to meet the market demand. This paper shows that the loading strategy of MDCS performance is better than the loading strategy of NCS in terms of AGV utilization and overall performance, which means that improving the utilization of AGV contributes to increasing the system’s production. The main attraction of this research Mousavi et al. (2017a, p. 58) was the use of a fuzzy hybrid genetic algorithm (GA)-particle swarm optimization (PSO) algorithm, with a comparison with three other algorithms (GA, PSO, and hybrid GA-PSO). A comparison of the results of the four algorithms showed that the FuzzyHybrid-GA-PSO yields the lowest production time and AGV numbers. However, a difference was observed between the performance of Fuzzy-Hybrid-GA-PSO and Hybrid-GA-PSO. The only significant improvement over Hybrid-GA-PSO was the computation time. The AGV system simulation with Flexsim software proved the practicality of the developed model and the studied algorithms.

This research Mousavi et al. (2017b, p. 1) focused on multi-objective AGV scheduling in a flexible manufacturing system (FMS) using GA, PSO, and hybrid GA-PSO algorithms. A model for the AGV task schedule was developed. Comparing the three algorithms shows that the hybrid GA-PSO provides the lowest production runtime and AGV numbers. It was found that after optimization, despite a slight increase in the total AGV running time (loaded and unloaded). Reducing the idle time of the AGVs improved the operating efficiency of the AGVs. Consistent with the experimental results, FlexSim software has been used to prove the developed model's feasibility and the optimization algorithms' suitability for the scheduling problem. The developed model can be applied to any FMS with different concepts. It can be used to optimize the objectives separately or combinatorial.

# 4 Concept

This chapter first introduces the research questions of this dissertation. Then, the overall and use case requirements are presented and compared to the research approaches to identify the scientific gap for this dissertation. After that, the development concept of the battery usage optimization service (BUOS) is described in this chapter. Last, the calculation model selection requirements are presented and compared to the existing calculation models. This subchapter ends with introducing the selected calculation model to validate the results of this dissertation.

## 4.1 Research Questions

The following research questions are addressed in this dissertation and derived below to achieve the mentioned objective target in chapter 1.3. The objective of this dissertation is to develop an ICT solution (a software service with an algorithm) to enable peak-shaving in companies so that the companies can save energy costs caused by peak loads. The main research question to answer in this dissertation is:

- **How should an algorithm-based ICT solution be designed to realize energy flexibility in manufacturing with peak shaving load control using AGV lithium batteries to enable cost savings for the companies during peak loads?**

The following sub-research questions, which are addressed in this dissertation, are:

1. What are the already developed concepts and approaches with battery technologies to realize energy flexibility in manufacturing using load control method peak shaving, and what are the challenges of using AGV lithium batteries as energy storage compared to these existing concepts and approaches?
2. What are the essential requirements to develop this solution for the AGV lithium batteries?

3. How should the algorithm-based ICT solution be developed to provide power cost savings by peak shaving in a manufacturing company while using AGV lithium batteries as energy storage?
4. How to validate whether any economic advantage is gained by using AGV lithium batteries to cover peak loads for the manufacturing companies?
5. How cost-effective is it for a manufacturing company to use AGVs along with this solution as energy storage and transport systems?

The overall and use case requirements compare the research approaches with the developed generic solution approach in this dissertation. To realize this comparison, first, the applications and concepts with different battery technologies, such as stationary, EV, and AGV, are described in chapter 3.1. Then the defined requirements are compared to the existing solution approaches in a matrix to define the scientific gap and the challenges.

The second sub-research question considers the essential overall and use case requirements. This question is answered in chapter 4.2, and its answer helped developing a generic solution to provide power cost savings and enable peak shaving in the company.

The generic solution approach (concept) is developed in chapter 4.3, and the realization of the ICT solution is introduced in chapter 5 to answer the third research question. The last two research questions evaluate the developed concept and the ICT solution. To respond to these questions, first, a sensitivity analysis is performed. The results of this analysis are compared to determine whether it is economical for a company to use AGVs both as energy storage and transport systems. The last two research questions are addressed in chapter 6.

## 4.2 Requirements

Considering the relevant fundamentals, the analysis of the state of the art in research and technology reveals many different research approaches for peak shaving with different battery usage. It is, therefore, necessary to examine the extent to which these approaches already answer the research question posed. First, overall and use case requirements are described in this chapter. Then, all requirements are compared to the existing research approaches to identify the scientific gap.

### 4.2.1 Overall Requirements

Two requirement categories can be identified to structure the overall requirements. These are requirements from the application context and the system architecture.

#### 4.2.1.1 Overall Application Context Requirements

The requirements from the application context describe which criteria must be met to be suitable for the intended application at the interface between the ICT solution and other systems such as AGVs, charging stations, and IT systems. The requirements list of the application context is illustrated in Table 4.1.

Table 4.1: Application context requirements list

| # | Requirements |
|---|---|
| **OAR1** | Definition of mathematical control algorithms |
| **OAR2** | Relevant object area representation |
| **OAR3** | Real-time interaction with other IT systems |
| **OAR4** | Automation of the control system |

(OAR1) Definition of mathematical control algorithms: To map the control system in software terms, the energy optimization of the AGV batteries must be described mathematically, and control algorithms must be formulated for finding solutions (see 2.6).

(OAR2) Relevant object area representation: First, defining the object area (scope) is necessary. The IT system should be able to calculate the optimal charging and discharging times for only AGV batteries according to the topic of this dissertation to enable peak shaving in manufacturing companies (see 2.3, 2.6 and 2.7).

(OAR3) Real-time interaction with other IT systems: Short reaction times are required to respond to high-frequency changes in manufacturing companies' energy consumption. It is essential for the IT system to perform optimizations for the usage of the AGV batteries in real-time (see 2.3 and 2.4).

(OAR4) Automation of the control system: The control system must be able to independently make decisions to control and regulate the charging and discharging times of AGV batteries. The decisions of the system are based on the combination of input data with the respective states of the system. Consequently, optimizing the energy consumption of production by reducing peak loads requires the highest possible level of automation (see 2.6).

#### 4.2.1.2 Overall System Architecture Requirements

From an IT perspective, the requirements for the system architecture define how the interaction of the ICT solution with existing related IT systems of a manufacturing company is designed and works. The requirements list from the system architecture is indicated in Table 4.2.

Table 4.2: System architecture requirements list

| # | Requirements |
|---|---|
| **OSR1** | Centralized control architecture |
| **OSR2** | Dynamical scalability |
| **OSR3** | Integration into existing production IT landscape |

(OSR1) Centralized control architecture: The centralized control architecture in production enables objects to process information and make decisions from a central component. This leads to a streamlining of planning and shifting of decisions in real-time. This avoids extensive and time-consuming computations and allows quick reaction to sudden changes (see 2.5).

(OSR2) Dynamical scalability: Production systems are dynamic systems that change over time. The centralized and automated ICT solution must accommodate new users and production data, such as AGV, charging station data, etc., to adapt to the production system (see 2.5).

(OSR3) Integration into existing production IT landscape: By acting at the interface between AGV control system and AGVs, it is necessary to provide for integration into the existing production IT landscape of manufacturing companies. Through machine-readable interfaces and corresponding data models, the ICT solution should be combined with the existing IT systems of manufacturing companies (see 2.4, 2.5 and 2.6).

### 4.2.2 Use Case Requirements

This chapter introduces the use case requirements to realize energy flexibility in manufacturing with peak shaving load control using AGV lithium batteries. Different research papers were inspected to derive requirements, and some experts working on the research projects were interviewed. The results are summarized in Table 4.3.

Table 4.3: Use case requirements list

| # | Requirements |
|---|---|
| **UCR1** | Focus on the industrial grid (manufacturing) |
| **UCR2** | Electricity cost and peak load reduction |
| **UCR3** | Usage of the AGV batteries |
| **UCR4** | Optimization of the AGV batteries charging schedule |
| **UCR5** | Service development as an ICT solution |
| **UCR6** | Running ICT solution in a software platform |
| **UCR7** | Consideration of renewable systems |
| **UCR8** | Bidirectional communication interface |

(UCR1) Focus on the industrial grid (manufacturing): The developed ICT solution should focus on the industrial grid so that the peak loads of a manufacturing company can be reduced and not negatively affect the existing production plan (see 2.4).

(UCR2) Electricity cost and peak load reduction: A manufacturing company's electricity cost and peak load should be covered and considered in the developed ICT solution so that the electricity cost of the same manufacturing company can be reduced (see 2.2 and 2.3).

(UCR3) Usage of the AGV batteries: An ICT solution should be developed in which the discharging schedule of the AGV batteries is defined so that the AGV batteries can be used to cover the peak loads and realize energy flexibility. The ICT solution should be a generic service for all AGV battery charging methods and schemes. The advantage of the usage of AGV batteries is that they usually have several AGVs, compared to stationary batteries that exist in manufacturing companies. On the other hand, the AGV batteries cannot be charged and discharged at any time like the stationary batteries because they have production schedule and route dependency. This dependency should be considered during the development of the ICT solution (see 2.6).

(UCR4) Optimization of the AGVs' batteries charging schedule: The charging schedule of the AGV batteries should be optimized so that the energy consumption of the AGV batteries can be reduced (see 2.6).

(UCR5) Service development as an ICT solution: A software service should be developed as an ICT solution to solve the peak load problem and reduce electricity costs (see 2.4 and 2.5).

(UCR6) Running ICT solution in a company platform: The ICT solution (software service) should be a part of a company platform so that different users can use it. A company platform is required for different IT systems' data storage and execution. Therefore, the hardware of a required data center should be available to enable it to run a company platform (see 2.4).

(UCR7) Consideration of renewable systems: Renewable systems can also support the electrical grid during peak load times. The ICT solution should be able to use and calculate the generated energy of renewable systems (see 2.2).

(UCR8) Bidirectional communication interface: The AGVs, charging stations, renewable energy sources, and production facilities (working stations) should work as the CPS (connectors to the company platform) and contain a bidirectional, IP-capable and push-capable communication interface and be able to transfer their data to a database (DB) in a company platform. The DBs should also have interfaces so that the data can be read and written to these DBs (see 2.4).

### 4.2.3 Requirements and Research Approaches Comparison

In this chapter, the research approaches are compared to the overall and use case requirements. The comparison of the overall requirements with the existing research approaches is indicated in Figure 4.1.

The results of Figure 4.1 show that Telaretti et al. (2016, p. 135), Tiemann et al. (2020, p. 112539), Zimmermann et al. (2020, p. 666) and Yesilyurt et al. (2021, p. 1) have done only theoretical work and presented any IT systems as part of their papers. The requirement OAR1 is considered by most of the researchers except 4 researcher papers mentioned above in their work because they needed the mathematical control algorithms to develop their IT systems. All researchers are presented relevant object area (OAR2) and showed the results of their developed methodologies and software systems in their relevant object areas. Most developed IT systems are simulations and blackbox IT systems that do not interact with other IT systems. That can be seen as a result that therefore most of the researchers did not consider the requirements such as real-time interaction with other IT systems (OAR3), automation of the control system (OAR4), centralized control architecture (OSR1), integration into existing production IT landscape (OSR3). The dynamical scalability (OSR2) is considered by the researchers except the research papers, which have done only theoretical work. The presented approaches from chapter 3.1 can fulfill only some of the described overall requirements from chapter 4.2.1.

| Research Approaches | OAR1 | OAR2 | OAR3 | OAR4 | OSR1 | OSR2 | OSR3 |
|---|---|---|---|---|---|---|---|
| Böttiger et al. 2018 | ● | ◐ | ○ | ○ | ○ | ◐ | ○ |
| Braeuer et al. 2019 | ● | ◐ | ◐ | ○ | ◐ | ◐ | ○ |
| Höne et al. 2019 | ● | ◐ | ○ | ○ | ○ | ◐ | ○ |
| Lehmann et al. 2016 | ● | ◐ | ○ | ○ | ○ | ◐ | ○ |
| Lu et al. 2018 | ● | ◐ | ● | ◐ | ◐ | ◐ | ● |
| Oudalov et al. 2007 | ● | ◐ | ● | ◐ | ◐ | ◐ | ● |
| Schulze et al. 2019a | ● | ◐ | ● | ◐ | ◐ | ◐ | ● |
| Telaretti et al. 2016 | ○ | ◐ | ○ | ○ | ○ | ○ | ○ |
| Tiemann et al. 2020 | ○ | ◐ | ○ | ○ | ○ | ○ | ○ |
| Werle et al. 2019 | ● | ◐ | ○ | ○ | ○ | ◐ | ● |
| Zafirakis et al. 2014 | ● | ◐ | ○ | ○ | ○ | ◐ | ○ |
| Zimmermann et al. 2020 | ○ | ◐ | ○ | ○ | ○ | ○ | ○ |
| Amamra et al. 2019 | ● | ◐ | ○ | ○ | ○ | ◐ | ○ |
| Hofmann et al. 2015 | ● | ◐ | ● | ◐ | ○ | ◐ | ○ |
| Raab et al. 2017 | ● | ◐ | ● | ● | ○ | ◐ | ○ |
| Bohács et al. 2021 | ● | ◐ | ○ | ○ | ○ | ◐ | ○ |
| European Commission 2019 | ● | ◐ | ● | ◐ | ◐ | ◐ | ● |
| Harnischmacher et al. 2021 | ● | ◐ | ● | ◐ | ◐ | ◐ | ● |
| Ihle et al. 2014 | ● | ◐ | ○ | ○ | ○ | ○ | ○ |
| Yesilyurt et al. 2021 | ○ | ● | ○ | ○ | ○ | ○ | ○ |

○ No fulfilment ◐ Partial fulfilment ● Fulfilment

Figure 4.1: Research approaches vs. overall requirements

Moreover, Figure 4.2 shows the results of the comparison between research approaches and the use case requirements. The comparison results indicate that most research approaches, except Ihle et al. (2014, p. 1), European Commision (2019) and Harnischmacher et al. (2021, p. 205) focused on reducing peak loads in industrial power grids. But the use of AGVs as energy storage was only considered by some of the approaches. From Böttiger et al. (2018, p. 102) to Zimmermann et al. (2020, p. 666), the researchers focused on the solution approaches with stationary batteries. From Amamra et al. (2019, p. 1) to Raab et al. (2017, p. 1), the researchers have developed IT systems for using EV batteries as energy storage to cover peak loads. The researchers from the Bohács et al. (2021, p. 294) to Yesilyurt et al. (2021, p. 1) have considered the usage of the AGV batteries (UCR3) and optimized the charging schedule of the AGV batteries (UCR4).

| Research Approaches | UCR1 | UCR2 | UCR3 | UCR4 | UCR5 | UCR6 | UCR7 | UCR8 |
|---|---|---|---|---|---|---|---|---|
| Böttiger et al. 2018 | ● | ● | ○ | ○ | ● | ○ | ○ | ○ |
| Braeuer et al. 2019 | ● | ● | ○ | ○ | ● | ◐ | ○ | ◐ |
| Höne et al. 2019 | ● | ● | ○ | ○ | ● | ○ | ○ | ○ |
| Lehmann et al. 2016 | ● | ● | ○ | ○ | ● | ◐ | ● | ○ |
| Lu et al. 2018 | ● | ● | ○ | ○ | ● | ◐ | ○ | ◐ |
| Oudalov et al. 2007 | ● | ● | ○ | ○ | ● | ○ | ○ | ● |
| Schulze et al. 2019a | ● | ● | ○ | ○ | ● | ◐ | ○ | ○ |
| Telaretti et al. 2016 | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ |
| Tiemann et al. 2020 | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ |
| Werle et al. 2019 | ● | ● | ○ | ○ | ● | ◐ | ○ | ● |
| Zafirakis et al. 2014 | ● | ● | ○ | ○ | ● | ◐ | ○ | ◐ |
| Zimmermann et al. 2020 | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ |
| Amamra et al. 2019 | ● | ● | ○ | ○ | ● | ◐ | ○ | ● |
| Hofmann et al. 2015 | ● | ● | ○ | ○ | ● | ◐ | ○ | ● |
| Raab et al. 2017 | ● | ● | ○ | ○ | ● | ◐ | ○ | ● |
| Bohács et al. 2021 | ● | ○ | ● | ◐ | ● | ◐ | ○ | ◐ |
| European Commission 2019 | ○ | ● | ● | ◐ | ● | ◐ | ○ | ● |
| Harnischmacher et al. 2021 | ○ | ● | ● | ◐ | ● | ◐ | ○ | ● |
| Ihle et al. 2014 | ○ | ○ | ● | ● | ● | ◐ | ○ | ● |
| Yesilyurt et al. 2021 | ● | ● | ● | ● | ○ | ○ | ○ | ○ |

○ No fulfilment ◐ Partial fulfilment ● Fulfilment

Figure 4.2: Research approaches vs. use case requirements

It can be observed that some software services have been developed by researchers only for their subject areas, which are more often simulations. Böttiger et al. (2018, p. 102) and Höne et al. (2019, p. 359) have developed black box systems such as simulations and Telaretti et al. (2016, p. 135), Tiemann et al. (2020, p. 112539), Zimmermann et al. (2020, p. 666) and Yesilyurt et al. (2021, p. 1) have done only theoretical work. As a result, these researchers did not consider requirements like running an ICT solution in a company platform (UCR6) and bidirectional communication interface (UCR8). Additionally, only Lehmann et al. (2016, p. 313) have considered the integration of renewable systems in contrast to the other research approaches.

This dissertation also aims at enabling peak shaving in industrial grids and has the same objective as the papers Lehmann et al. (2016, p. 313), Lu et al. (2018, p. 2) and Oudalov et al. (2007, p. 621). Instead of stationary batteries, AGV batteries are used. In this dissertation, contrary to Braeuer et al. (2019, p. 1424), only the revenue stream peak shaving is considered. Instead of BSS, the AGV batteries are used to take advantage that AGVs are already operating in manufacturing, which can be used as energy storage in their idle times. Similar techno-economic analysis which is mentioned in Höne et al. (2019, p. 359) is applied in this work. The difference is the usage of the battery technology. Furthermore, this dissertation investigates the combination of the DSM scenario peak shaving with the AGV batteries instead of the BSS, which is considered in Schulze et al. (2019a, p. 683). According to the findings of Telaretti et al. (2016, p. 135) Zimmermann et al. (2020, p. 666), lithium battery technology is most effective for peak shaving applications compared to other battery technologies. Therefore, only the AGVs are considered in this dissertation which consist of lithium batteries. Moreover, an ICT solution is developed in this dissertation in considering the findings of Tiemann et al. (2020, p. 112539) to reduce the electricity cost of the industrial grid with the usage of AGV batteries. In contrast to Werle et al. (2019, p. 482), it is not relevant in this dissertation to choose a battery with sufficient capacity, because already operating AGVs are considered, which are used to enable peak shaving in the manufacturing plants. Additionally, the investment in the new energy storage is not relevant in this work, which was considered in Zafirakis et al. (2014, p. 178). Nonetheless, the battery degradation of the AGVs is taken into account during the development of the ICT solution in this dissertation. The profitability of the presented solution in this work is related to the AGV battery system lifetime.

This dissertation pursues a similar objective as Amamra et al. (2019, p. 1), Raab et al. (2017, p. 1), but the AGV-batteries are considered instead of EV batteries in this work. In addition, an algorithm is developed in this dissertation like in Hofmann et al. (2015, p. 4). The algorithm is based on a bidirectional charging concept of the AGV batteries instead of the EV batteries.

The main difference between AGV and EV batteries is availability. The AGVs should accomplish their production tasks and is not always available.

European Commission (2019), Harnischmacher et al. (2021, p. 205) and Ihle et al. (2014, p. 1) used AGV batteries which are working as transport vehicles in a port to realize peak shaving in the electricity grid. However, an industrial grid is not considered in these papers. This dissertation aims to reduce peak loads in the manufacturing plants with the AGV batteries that are a part of the manufacturing. Although Yesilyurt et al. (2021, p. 1) has the same aim as this dissertation, they have done only the theortical work. The development of an ICT-solution and result validation were not a part of this paper. Bohács et al. (2021, p. 294) built a simulation model for the implementation of planning and energy efficiency aspects in production logistics using AGV systems. However, peak shaving is not considered in this paper.

It can be interpreted from the results that enabling energy flexibility in manufacturing with peak shaving load control using AGV lithium batteries has yet to be considered by other researchers. Therefore, this dissertation aims to cover this scientific gap and realize it by developing and using an ICT solution.

From the research approaches, the following points are considered for developing this dissertation's ICT solution. Telaretti et al. (2016, p. 135) found that lithium battery technology is more effective for peak shaving applications than other battery technologies. Moreover, according to the findings of Zimmermann et al. (2020, p. 666), lithium battery technology is one of the cost-effective battery technologies to be used in the peak shaving application. Therefore, only lithium batteries are considered in this dissertation as an energy source for AGVs.

The designed concept and the service realization are presented in the following chapters to fulfill all requirements.

## 4.3 Concept Description

The methodical procedure is first shown in this chapter. Second, the concept picture is described from the company side, and the dissertation's focus is presented. Then, the BUOS is related to RAMI 4.0 model, and the BUOS design model is introduced.

### 4.3.1 Methodical Procedure

The development of the ICT solution in this dissertation is approached methodically, according to the waterfall modell of Lauber et al. (1999, p.61) (see Figure 4.3).

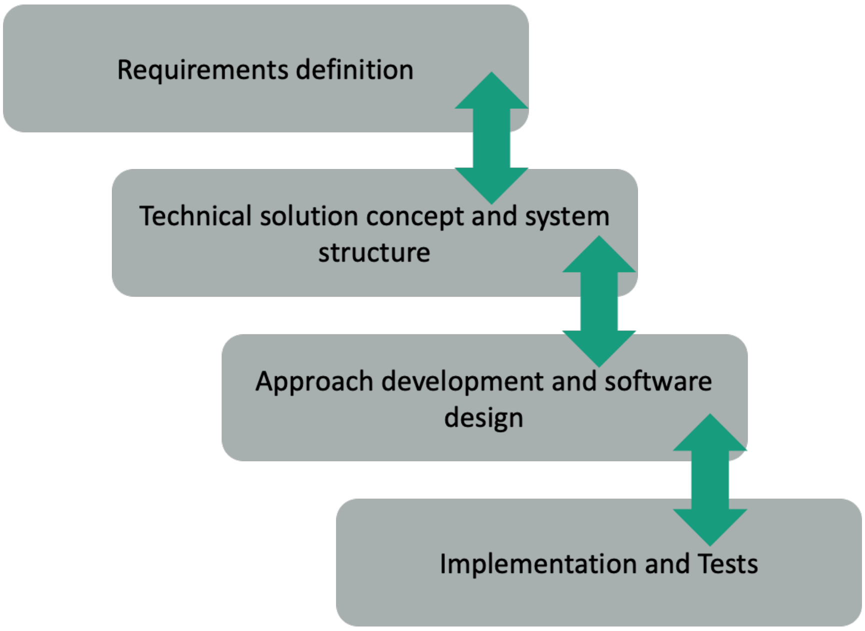



Figure 4.3: Solution development according to Lauber et al. (1999, p. 61)

The aim is to develop an ICT solution for scheduling the charging and discharging times of AGV batteries to cover peak loads in manufacturing. The first step is to define the requirements placed on the system to be developed (see chapter 4.2). In the next step, a technical solution concept is developed with consideration whether the proposed solution concept meets the requirements. After that, the software design (BUOS design model) and the approach development (BUOS algorithms and working steps) are presented. Finally, BUOS implementation is conducted and implemetation tests are carried out.

### 4.3.2 Technical Solution Concept and System Structure

Figure 4.4 depicts the overall concept picture from the view of a manufacturing company using BUOS. Two different environments, such as the company service platform and the company shop floor, are observed in the concept picture.

The company service platform is used for the data storage and execution of the IT systems and assets (BUOS, charging stations, AGVs). It can be a cloud or edge platform. This platform should enable the BUOS to communicate to the DBs (described as Data Aggregation in the concept picture). The company shop floor describes the physically existing equipment of the production, such as production facilities, charging stations, and AGVs. Additionally, external factors for a manufacturing company, such as renewable energy sources and electricity prices, are displayed in this picture. To enable the BUOS to work, the following data is required: Market electricity prices and special tariff models (contractual price models depending on the highest peak production load), power data from renewable energy sources and from the production facilities, charging station data and AGV data.

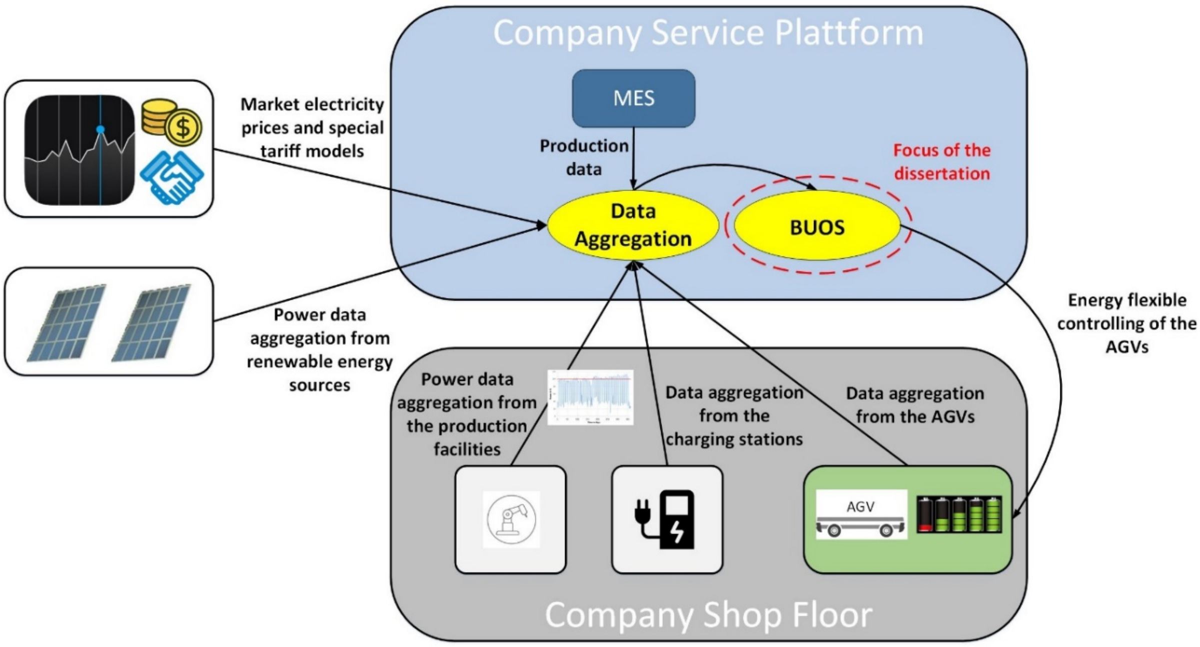



Figure 4.4: Concept picture from the company side

Only AGVs with lithium battery technology should be considered in this dissertation because lithium batteries offer a higher capacity respectively, a higher number of charge cycles (Ullrich et al. 2019, p. 100), and are most effective for peak shaving applications compared to other battery technologies (Telaretti et al. 2016, p. 135) (Tiemann et al. 2020, p. 112539). Additionally, according to the study, lithium batteries are most suitable for peak shaving applications (Zimmermann et al. 2019, p. 74). The SOC of all AGVs should remain between 20 and 90 % so that the batteries can be conserved. AGV lithium battery operation ranges (SOC limits) are set concerning the paper results (Altaf et al. 2017, p. 49).

### 4.3.3 BUOS Design Model

This work focuses on the development of the ICT solution BUOS. The BUOS gathers all the data illustrated above and creates a charging and discharging scheduling for the AGV batteries to reduce peak loads. The following section describes why RAMI 4.0 was chosen as a design model for the BUOS.

A primary goal of RAMI 4.0 is to use Industry 4.0 to specify a generally valid data model that all participants of Industry 4.0 use. This eliminates the need for complicated, cost-intensive, and error-prone parallel structures, including unnecessary data transfers. Only the standard semantics enable data consistency between companies' shop and office floors (Heidel et al. 2017, p. 4).

RAMI 4.0 ensures that all participants, such as AGVs or production machines in Industry 4.0, share a common perspective and build a common understanding. The BUOS benefits from Industry 4.0, creates connectivity between all devices and will be a component of Industry 4.0. Therefore, it is designed according to RAMI 4.0 (see Figure 4.5).

**RAMI 4.0 Layers of the BUOS:**

The RAMI 4.0 layers consist of business, function, information, communication, integration, and asset, all of which are used in the conceptual structure of the BUOS.

**The asset layer** reflects the physical world (Heidel et al. 2017, p. 46). The five other layers are located in the information world. The hardware of the AGV is a part of the asset layer, whose data is used by the BUOS.

**The integration layer** is the link between the physical world of an asset and the information world of Industry 4.0 (Heidel et al. 2017, p. 46). CPS on the AGV is part of the integration layer, a piece of hardware. Still, it communicates to a DB server via its bidirectional IP-capable, push-capable communication interface. It collects the energy data from the AGV lithium batteries and the position data of the AGV.

**The communication layer** describes the communication interface of an asset (Heidel et al. 2017, p. 47). Transmission Control Protocol (TCP) and Internet Protocol (IP) were defined as transmission protocols. The recommended and prescribed communication protocols (TCP/IP) are applied in this concept.

**The information layer** combines an asset's relevant data and characteristics (Heidel et al. 2017, p. 50). It stores the data associated with the functions, including their location, e.g., in a cloud or an edge server. The relevant data, which is stored and collected in this concept, is energy data of the lithium batteries, availability data, and position data of the AGVs.

**The function layer** contains all functions and services that match Industry 4.0 standards (Heidel et al. 2017, p. 51). They obtain their information from the Industry 4.0 data of the information layer and store the results as Industry 4.0 data in the information layer. The BUOS is assigned in the function layer of RAMI 4.0.

**The business layer** describes the business procedures and conditions for an asset or an Industry 4.0 application (Heidel et al. 2017, p. 53). In this work, the energy management of the lithium batteries of AGVs to reduce electricity costs for companies is defined as a RAMI 4.0 business layer.

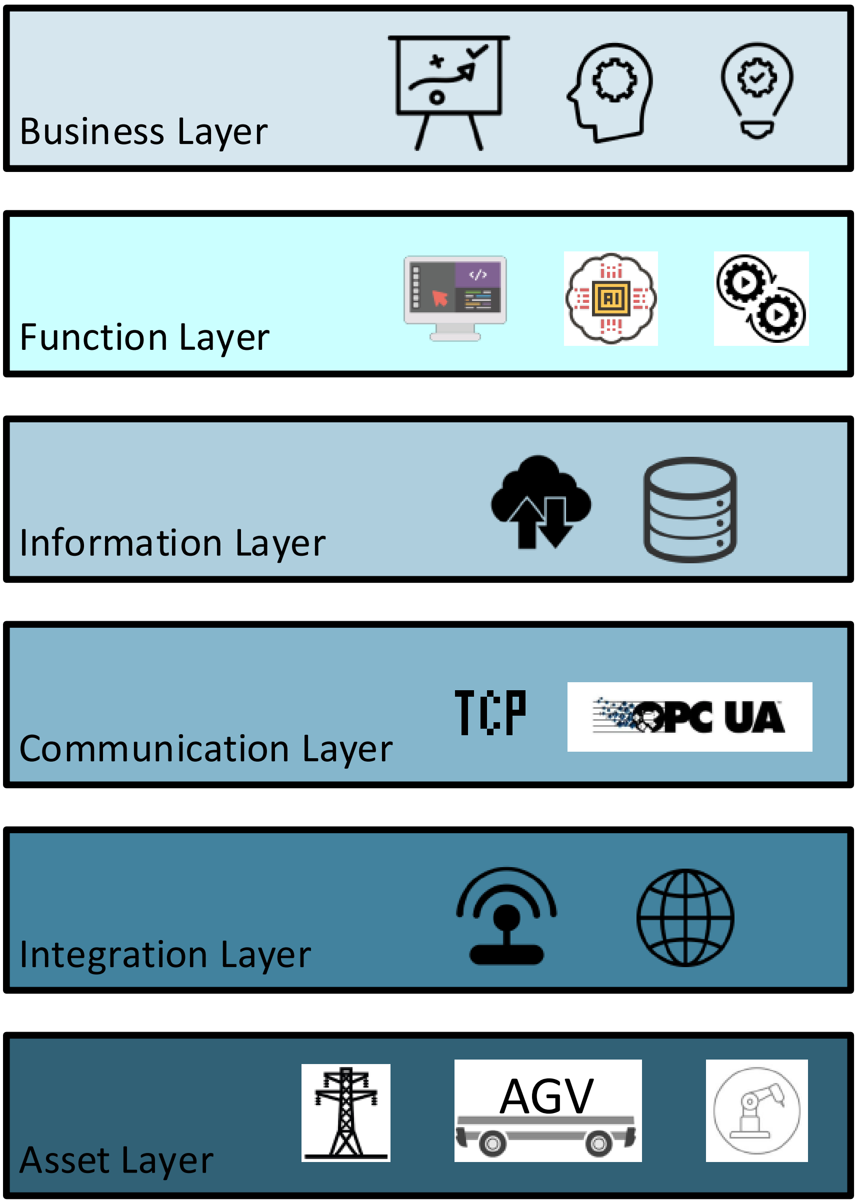



Figure 4.5: RAMI 4.0 concept for the BUOS

**RAMI 4.0 hierarchy levels of the BUOS:**

The hierarchy axis is used for vertical integration, e.g., it describes the levels of a factory (Heidel et al. 2017, p. 44). However, since Industry 4.0 is also intended to operate beyond the physical boundaries of the factory, logistics and transport networks from the supplier to the customer should be integrated, which describes the top level of the hierarchy, the "Connected

World." The BUOS should communicate with the production machines and charging stations. Therefore, the BUOS is assigned to the Connected World hierarchy level of RAMI 4.0.

**RAMI 4.0 Life Cycle and Value Stream of the BUOS:**

They consist of two phases. The first phase represents the development of an asset from the initial idea to the prototypes and testing (Heidel et al. 2017, p. 43). The production of an AGV can be given as an example. The second phase comprises the production of the previously developed asset with its usage (service) (Heidel et al. 2017, p. 43). In this phase, the development of the BUOS for the energy management of AGV batteries can be associated.

### 4.3.4 BUOS Algorithm and Working Steps

After the BUOS is designed according to the RAMI 4.0 model, a concept for the BUOS is developed, which enables an optimal AGV battery charging and discharging schedule. The concept of the BUOS consists of three different working steps. Figure 4.6 represents the algorithm of the BUOS model. The algorithm is designed according to the DIN 66001 standard. In this standard, the program flow chart symbolically describes, by using symbols, the sequence or order of logical operations necessary to solve problems (Hering 1984, p. 26).

In the first step, peak load times are identified using energy consumption, renewable energy generation, and peak power during production. Energy consumption data is subtracted from renewable energy data. The result is compared with the company's predetermined peak power limit and the times in which the result was higher than the agreed peak power limit was defined as peak load times. In the following working step, the data of the AGV routes, the AGV battery energy consumption, the AGV charging, working, and idle times are used to find out the availability of the AGV. A decision mechanism for the charging and discharging schedule determines when the AGV battery should be charged and discharged in consideration of battery degradation (cycle aging is considered in this dissertation), availability of the AGVs, and charging station occupancies without negatively affecting the existing production situation. The peak load times and AGV states are temporarily stored in third step and adjusted after each calculation of the time points. This decision was made to optimize the speed of the algorithm to avoid unnecessary double calculations. After calculating all time points, both peak load times and AGV states are updated in the databases.

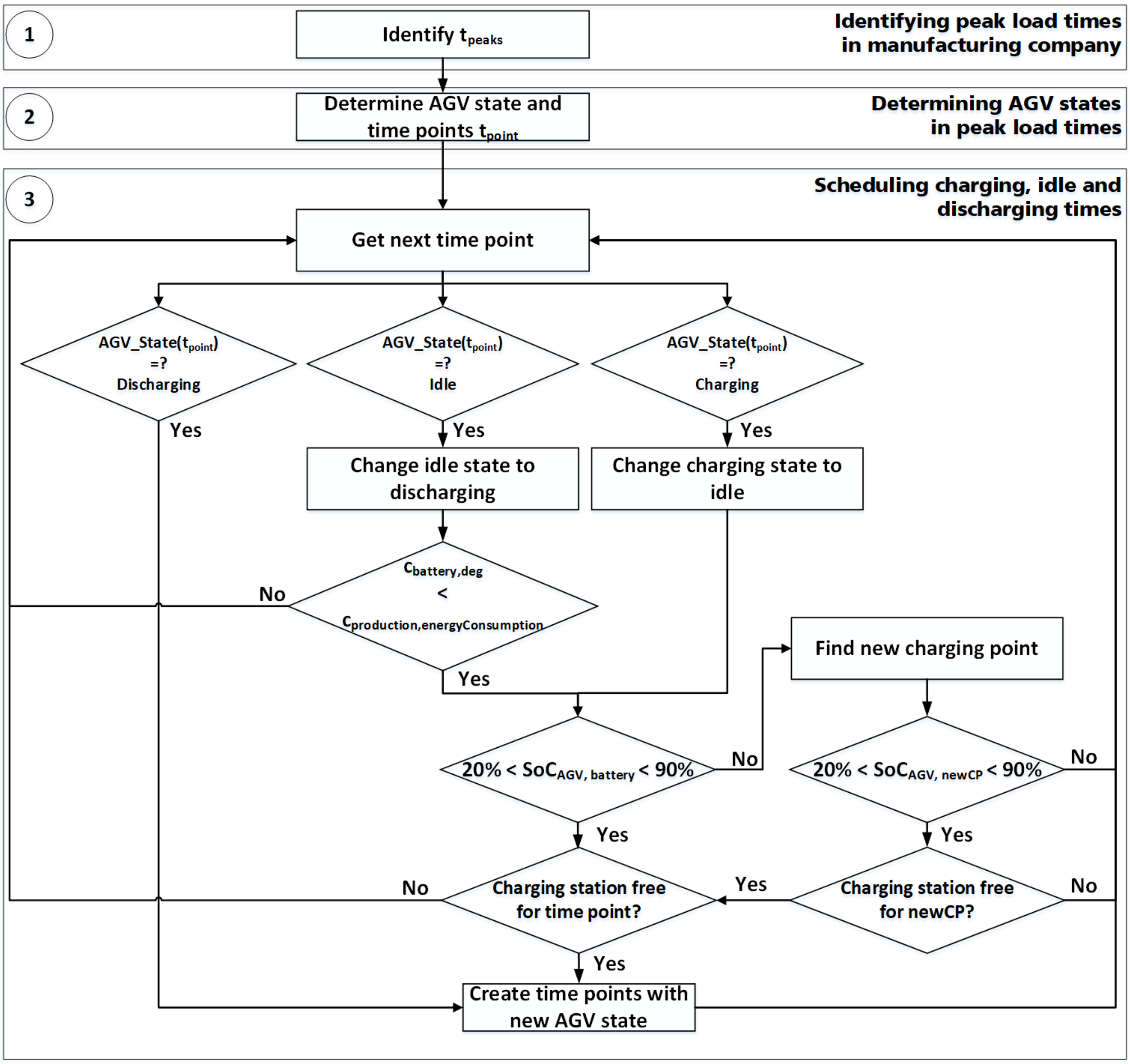



Figure 4.6: The algorithm of the BUOS model

The first AGV states during peak load times are identified to calculate the final time points. Then the AGV states are compared at the time points. If an AGV state is discharging, the time point is set as discharging time. When an AGV state is idle in peak load times, it is verified whether this time can be converted to discharging, so the power from the AGV battery provides that part of the peak loads in the manufacturing company.

Three following conditions (see Figure 4.6) are examined here. First, the battery degradation caused by discharging should be lower than the energy cost of an energy consumer in the manufacturing company. The second condition is that the current SOC of the AGV battery should remain between 20 and 90 % to maintain the battery lifetime. As the last condition, the charging station or plate must be available. If the AGV state is charging, it is verified if this time can be converted to idle so that during peak load times, no power is used for charging the AGVs from the manufacturing company grid. In this case, only two conditions are checked. If the SOC of the AGV battery is not in the range of 20-90 % after the adjustment of the AGV state, a new charge point is sought so that the SOC can be kept inside the predefined limits. After checking that a new time point can be used as a charge point, the original charge point is scheduled as an idle point.

Once all conditions for charging, idle and discharging times are fulfilled, the decision mechanism of the BUOS determines when the AGV battery should be charged and discharged without negatively affecting the existing production plan.

The parameters which are used in the algorithm of the BUOS model are depicted in Table 4.4.

Table 4.4: Parameter description of BUOS model's algorithm

| Abbreviation | Parameter description |
|---|---|
| **AGV_State** | State of an AGV battery (1: charging, 0: idle, and -1: discharging) |
| $\mathbf{c_{battery,deg}}$ | Degradation costs of an AGV battery |
| $\mathbf{c_{production,energyConsumption}}$ | Energy consumption costs of a manufacturing company |
| $\mathbf{SoC_{AGV\_battery}}$ | State of charge of an AGV battery |
| $\mathbf{SoC_{AGV\_newCP}}$ | State of charge of an AGV battery in a new charging point |
| $\mathbf{t_{peaks}}$ | Peak times of a manufacturing company |
| $\mathbf{t_{points}}$ | Times at which the AGV is available and not working |

## 4.4 Calculation Model Selection

This chapter aims to find a suitable method to evaluate the cost-effectiveness of the developed software that reduces electricity costs. The initial question is the fourth research question, therefore, as follows:

- How to validate whether any economic advantage is gained by using AGV lithium batteries to cover peak loads for the manufacturing companies?

To answer this question, the following question should be answered: Which models for an investment calculation exist and which are relevant for the defined use cases?

After answering this question, one of the models found to be relevant will be selected. Subsequently, the following question should be answered:

- How is the relevant model performed or calculated?

First, the requirements for calculation model selection are introduced. Then, the reasoning behind which model is considered a validation method in this work is described. Last, the relevant selected model is presented in the last subchapter.

### 4.4.1 Requirements for Calculation Model Selection

To select a suitable calculation model to validate the results of this dissertation, the following requirements are defined (see Table 4.5):

Table 4.5: Requirements list for calculation model selection

| # | Requirements |
|---|---|
| **CR1** | The evaluation target is achievable |
| **CR2** | Results from varied scenarios representable |
| **CR3** | Economic feasibility of investing in new assets |

(CR1) The evaluation target is achievable: The cost savings of a manufacturing company, which uses its AGV batteries in production to cover the peak loads of its industrial grid, should be calculated by the calculation model to find out how economical the use of AGV as energy storage with the developed service is (see 2.9).

(CR2) Results from varied scenarios representable: The results from varied scenarios in different use cases (companies) should be validated by the calculation model (see 2.9).

(CR3) Economic feasibility of investing in new assets: The calculation model should enable the calculation of whether it is economical for companies to invest in new assets like AGVs and charging stations for peak-shaving purposes (see 2.9).

### 4.4.2 Requirements and Calculation Models Comparison

This chapter compares calculation models that partially or fully meet the identified requirements. The results are indicated in Figure 4.7.

The profitability calculation (also profitability comparison calculation) calculates the ratio of a success variable (e.g., profit) to a capital input variable. Although, they can be partially used to achieve the evaluation target. The investment decision of AGV procurement has yet to be realized for using AGV as energy storage. Therefore, they did not be selected for validating the developed service. Some other models can provide the possibility to calculate the economic feasibility of investing in new assets like AGVs. Still, the first two requirements cannot be fulfilled by these models. The calculation models can fulfill only some of the described requirements. The calculation model “sensitivity analysis” has the highest coverage ratio. Therefore, the sensitivity analysis is chosen as a validation method by the author of this work to validate the developed software. With the help of the sensitivity analysis, it is investigated which parameters affect the investment and how the investment is optimized with modification of these parameters for implementing the developed software in different use cases.

| Calculation models | CR1 | CR2 | CR3 |
|---|---|---|---|
| Profit comparison calculation | ◐ | ◐ | ○ |
| Profitability calculation | ◐ | ◐ | ○ |
| Static amortization calculation | ○ | ○ | ● |
| NPV method | ○ | ○ | ◐ |
| Horizon value method | ○ | ○ | ◐ |
| Dynamic amortization calculation | ○ | ○ | ● |
| Debit interest rate method | ○ | ○ | ◐ |
| Dean model | ○ | ○ | ◐ |
| Models for service life, replacement time and investment time decisions | ○ | ○ | ◐ |
| Sensitivity analysis | ● | ● | ○ |

○ No fulfilment ◐ Partial fulfilment ● Fulfilment

Figure 4.7: Calculation models vs. requirements

### 4.4.3 Selected Calculation Model Sensitivity Analysis

This chapter first introduces the definition of sensitivity analysis. Then, the performing the sensitivity analysis is described.

#### 4.4.3.1 Definition

Sensitivity analysis can be defined as "the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" (Saltelli et al. 2004, p. 45). Thus, sensitivity analysis indicates whether and how sensitive a real system is to certain changes (Cullen et al. 1999, p. 39). More specifically, sensitivity analysis provides information on how the output of a model reacts to the variation of input variables (Fassò 2006, p. 2). In this regard, sensitivity analysis can identify and control the most critical risk factors (Frey et al. 2002, p. 554) (Cullen et al. 1999, p. 39). The scientific literature has already applied the method to various examples from engineering, economics, physics, and many more (Frey et al. 2002, p. 554).

#### 4.4.3.2 Procedure Description

The following description of the procedure for conducting a sensitivity analysis is based on (Saltelli et al. 2004, p. 45):

1. Define the objective:
    a. Formulate the overall goal of the analysis: What question does the analysis seek to answer?
    b. Identify a suitable output function that can adequately answer this question.
2. Determine input factors:
    a. Which variables have an impact on the output function?
3. Selection of the method of sensitivity analysis:
    a. Conducting the nominal range sensitivity method

Since, in the given case, the sensitivity analysis is to be applied for a deterministic, linear relationship without probabilities, the nominal range sensitivity method (also called local sensitivity analysis or threshold analysis) (Frey et al. 2002, pp. 557–558) is suitable for this purpose.

In the nominal range sensitivity method, changes in the model's output are determined by varying a single input variable in the plausible range (Cullen et al. 1999, p. 270). Here, the plausible range is the maximum or minimum value based on a reference or nominal value (Siebertz et al. 2017, p. 72). All other input variables remain at their initial value and are unchanged (Cullen et al. 1999, p. 270). Therefore, all input variables are examined without considering correlations between the variables (ceteris paribus assumption) (Siebertz et al.

2017, p. 72). An example of the nominal range sensitivity method with one variable is shown in Table 4.6.

Table 4.6: Nominal range sensitivity method with one variable

| | Value Range | Output-Variable 1 |
|---|---|---|
| Varied input variable | **Minimal value** | |
| | **…** | |
| | **Maximal value** | |

4. Select the input example
5. Evaluate output, draw conclusions about the goal in step 1 and, if necessary, start a new iteration of the analysis.

# 5 Realization

The service description and development concept are first introduced in the realization chapter. After the service instantiation and working procedure are described, the performed software tests and the results of these tests are represented. After that, the service deployment in a manufacturing company is described. Last, the benefits of the developed and deployed service are highlighted at the end of this chapter.

## 5.1 Service Description

This chapter describes the working steps of the BUOS in more detail. The BUOS does not control AGVs and charging stations. It only creates a scheduling option, how AGV should be charged or discharged, and displays the results to the production planner. If the production planner uses the scheduling option, the scheduling information is sent to the AGVs. It is shown in Figure 5.1 that the BUOS (rectangle marked in green) has three working steps, which are introduced with an algorithm in Figure 4.6. This chapter aims to enhance and describe the three working steps in more detail. The BUOS works in all AGV battery charging methods and communicates to the production system to detect the production systems' peak energy consumption. It is a generic solution that can be applied in production with different charging schemes and technologies.

The first working step of the BUOS gathers the historical and current data on the energy consumption of the production machines, energy generation of the renewables, and electricity prices. Then the peak and not peak loads of the production and current energy consumption of production machines and energy generation of the renewables in the manufacturing company can be determined with this data, and an energy consumption graph during one production year can be created. Thus, the peak load times in production are detected.

The first working step can be implemented in all charging methods because charging methods do not influence the identifying peak load times of a manufacturing company.

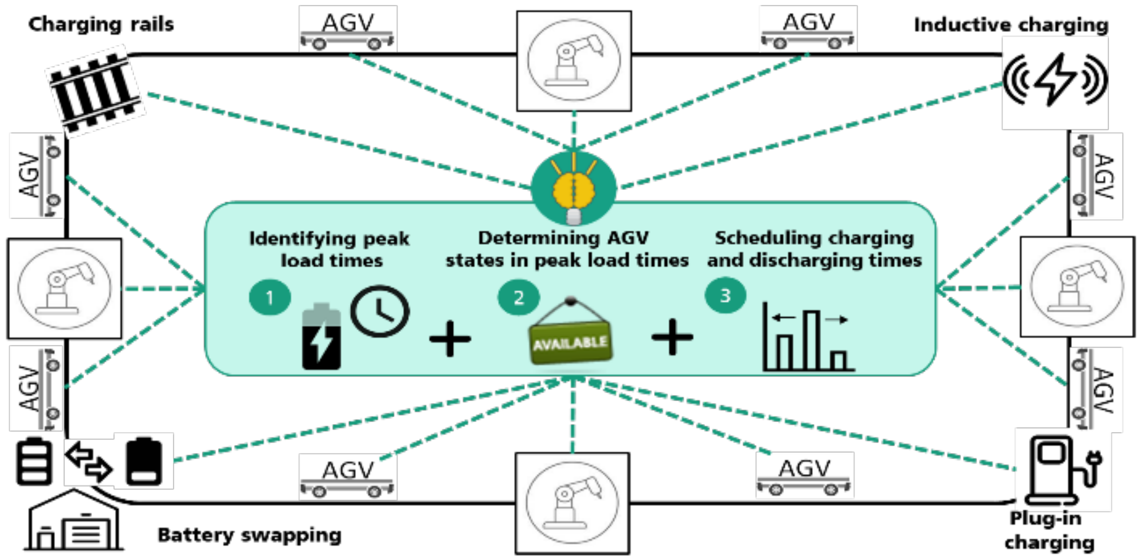



Figure 5.1: BUOS for AGV battery charging and discharging scheduling

In the second working step, the historical and current data of the AGV routes, the AGV battery capacity consumption, the charging times, stand-by, and possible charging times are used to determine the AGV state in peak load times. The algorithm is to be developed only to consider the possible charging time for plug-in (conductive) charging and hybrid charging. The possible charging time should not be considered for the other charging methods because the AGV battery does not have to be connected to the charging station. The AGV battery can be charged or discharged while it is moving. The optimal charging and discharging times for the AGV battery are calculated in the third working step. The decision mechanism of the BUOS verifies the three conditions mentioned in the concept chapter depending on the AGV state. The three conditions are the same for all charging methods. Therefore, the last working step can be implemented in all charging methods.

The third working step of the BUOS optimizes the charging and discharging times. With optimal charging and discharging times, cost-effective coverage of a working step of the production energy loads (peak shaving) can be enabled, and manufacturing companies can reduce their electricity costs. In this step, the BUOS can work with the battery-swapping charging scheme because AGV batteries are always available and plugged in at a charging station. AGV batteries can be used by the BUOS for the charging and discharging scheduling.

The BUOS contains features of the two charging schemes, such as opportunity and automatic charging. Contrary to opportunity charging, the BUOS lets the AGV batteries charge whenever there are no load peaks. Furthermore, the BUOS has no predefined SOC lower limit like automatic charging. The SOC of AGV batteries always remains between 20 and 90 %. Therefore, it can be stated that the BUOS is an optimized version of combination charging.

## 5.2 Service Development Concept

The BUOS is developed according to the Model View Controller (MVC) concept (see Figure 5.2). MVC is a concept that divides software into three categories (data model "model," presentation "view," and program control "controller"). The **model** controls the behavior and data of application services, processes requests for information about its state, and responds to commands to change the state (Burbeck 1992, p. 2). The **view** manages the graphical and textual output on display associated with its application (Burbeck 1992, p. 2). The **controller** interprets the user's mouse and keyboard input and instructs the model and view to change accordingly (Burbeck 1992, p. 2).

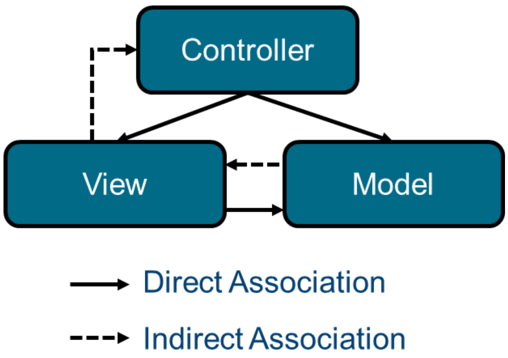



Figure 5.2: MVC concept

The BUOS works as a controller and has the task of determining the charging and discharging times of the AGVs and creating a scheduling option for the AGVs. It communicates with the data models described below and uses the data stored in MySQL and InfluxDB. Moreover, the BUOS has no general user interface (GUI) (View).

To develop the BUOS, the programming language Java is used. The BUOS requires continuous (time series) data with timestamps, such as energy consumption of the manufacturing company, as well as discrete data, such as maximum and minimum SOC values of AGV battery, to operate. According to the work of (Hao et al. 2021, p. 597), InfluxDB performs the best in compression, writes data at high concurrency, and processes queries faster than the other time series DBs. Therefore, it is decided to use InfluxDB to store and use the required time series data for the BUOS. To handle the discrete data, relational DB -MySQL- is used by the BUOS. Because MySQL has some good features such as speed, ease of use, query language support, and capability compared to other relational DBs (DuBois 2013, p. 4). The BUOS is also part of a cloud platform, so it can communicate to the AGV software and DBs via the middleware of the cloud platform. The BUOS also provides Representational State Transfer (REST) Application Programming Interface (API) so that its datasets can be read or written via a REST communication protocol.

## 5.3 Service Instantiation

In the service instantiation chapter, first, the developed classes of the service and the implemented algorithms and calculations for these service classes are described. After that, the external interfaces and the used data models are indicated in detail. Last, the implemented MSB events and functions of the service are explained.

### 5.3.1 Service Structure

The service structure of the BUOS is described in this chapter. The BUOS is instantiated in the cloud platform ESP. The mission of the ESP is to address the challenges of building a holistic IT solution and automate and standardize the entire process of energy flexibility trading from the machine to the energy market (Bauernhansl et al. 2019, p. 250). The core of ESP is represented by services to process, aggregate, and exchange data and evaluate and provide energy flexibility (Bauernhansl et al. 2019, p. 250).

ESP is divided into two sub-platforms, the company-side platform and the market-side platform, capable of data exchange and interaction via an interface (Bauernhansl et al. 2019, p. 251). The ESP describes the interaction of several enterprise platforms with a central market platform to perform IT-supported energy flexibility trading transparently (Bauernhansl et al. 2019, p. 251).

The BUOS communicates to the other IT systems and DBs via the middleware of the ESP “Manufacturing Service Bus” (MSB). Therefore, the BUOS contains a cloud middleware MSB interface. The MSB is a uniform integration layer for all sensors, actuators, machines, plants, IT systems, and services. So-called integration flows can define which data and information are forwarded to registered components (Schel et al. 2018a, p. 829). The MSB is hosted in the company-side platform of the ESP.

The communication between the BUOS and other IT systems is built by sending events and receiving functions in MSB. The BUOS has an MSB client, which sends the data with MSB events to other IT systems and gets its data from other IT systems through MSB functions. The BUOS is developed with the Java programming language. Figure 5.3 depicts the overall structure of the BUOS in the Java environment.

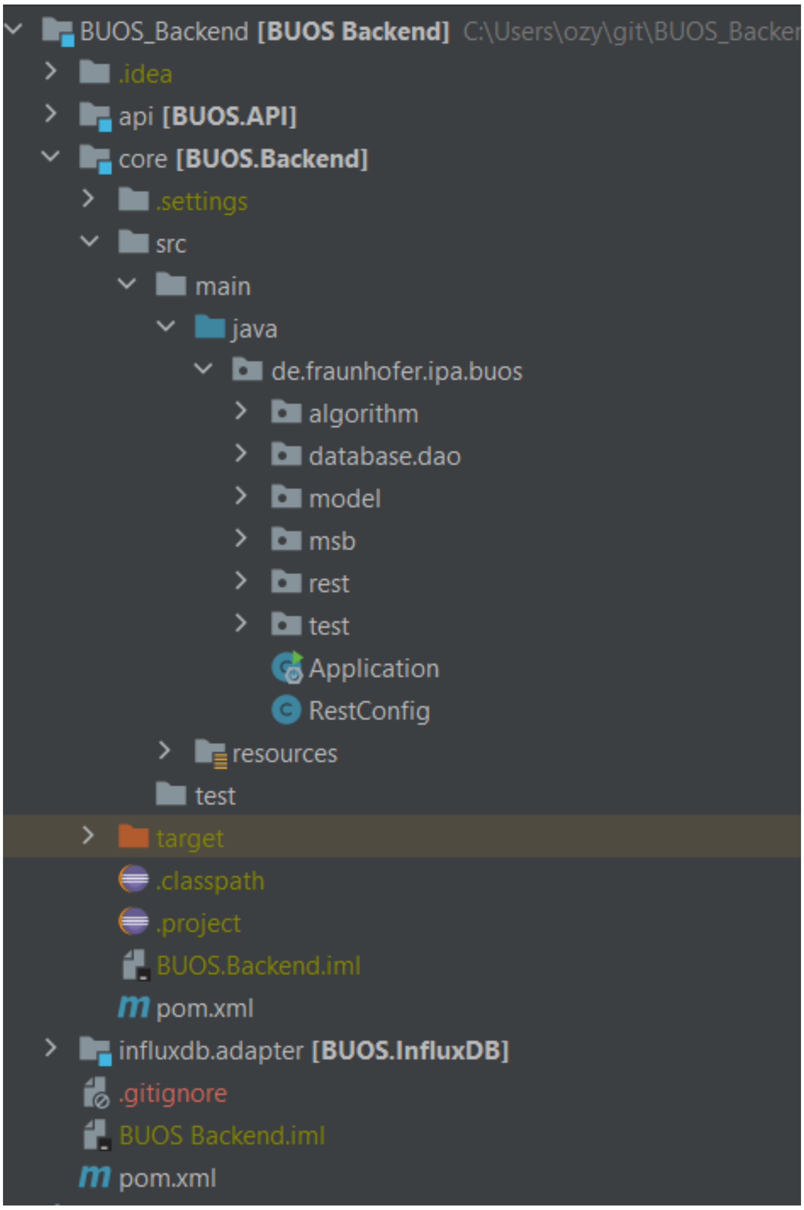



Figure 5.3: The BUOS service structure

The BUOS contains three main packages. These are:

- api: The "api" package describes the MySQL data model of the BUOS explained in the following chapters. The data model is used by the classes of the "core" package.
- core: The "core" package has the main task of controlling the BUOS and communicates to the "api" and "influx.adapter" packages. It consists of six sub-packages:

  - algorithm: This package consists of three main classes, which calculate the charging and discharging time points of a chosen AGV.
  - model: In this package, data models of different BUOS classes exist.
  - database.dao: That package has the software components that connect to MySQL DB, which can process the data and communicate to the “api” package.
  - msb: This package contains the classes communicating to the cloud platform. It communicates to the “algorithm” package to send the AGV data and get the charging and discharging schedules of the AGVs.
  - rest: It consists of a class that enables the connection to the MySQL DB of the BUOS via REST protocol and communicates to the “api” package.
  - test: The test classes are stored in this package, which is explained in more detail in subsequent chapters. It communicates to the “algorithm” and “msb” packages so that the tests can be executed for different main classes of the “algorithm” and “msb” packages.
- influxdb.adapter: The classes of this package allow the BUOS to communicate to the InfluxDB so that the relevant data can be read or written in real time.

### 5.3.2 Service Classes

The BUOS consists of the AlgorithmManager class of the “algorithm” package, which is responsible for the communication between the subclasses and the cloud interface class MSBEventHandler of the “msb” package (see Figure 5.4).

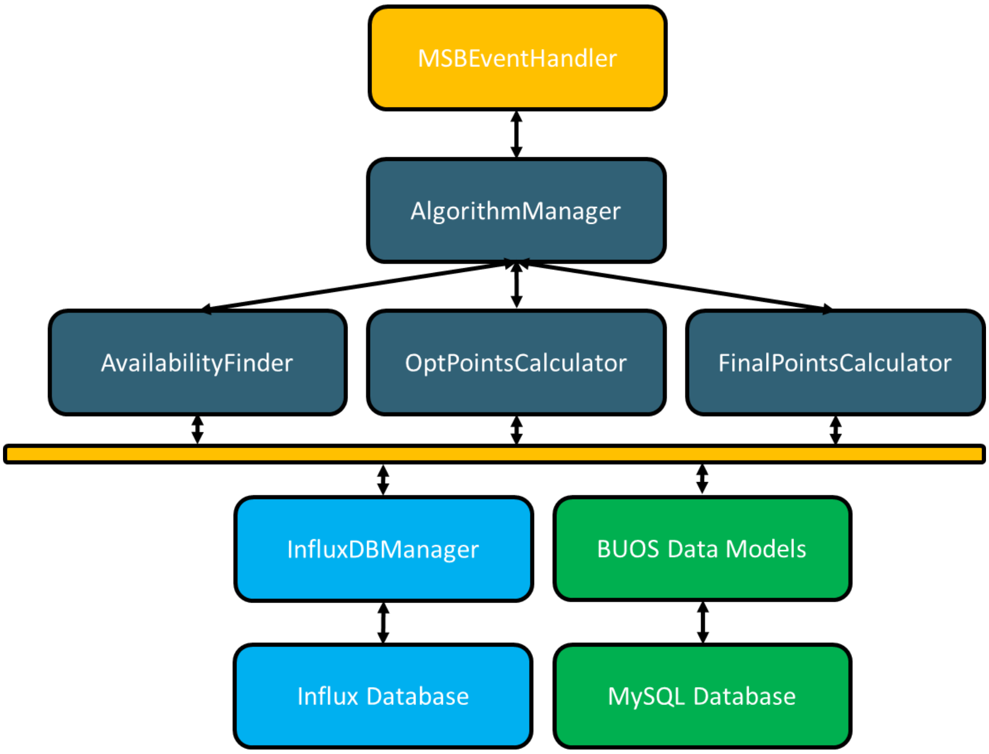



Figure 5.4: The BUOS classes

The subclasses are described below:

- **AvailabilityFinder:** The available times of the AGV batteries are found.
- **OptPointsCalculator:** Based on the energy consumption during production and the availability of AGV batteries, the charging, idle and discharging times (AGV states) in peak times are identified.
- **FinalPointsCalculator:** A decision mechanism for the charging and discharging schedule determines when the AGV battery should be charged and discharged in consideration of battery degradation (cycle aging), availability of the AGVs, and charging station occupancies without affecting the existing production situation negatively.

Other subclasses are presented below:

- **InfluxDBManager** offers other classes the possibility to communicate with the InfluxDBAdapter class. InfluxDBAdapter has the task of either reading the data from the InfluxDB or storing or deleting the data in the InfluxDB. Both classes are parts of the “influxdb.adapter” package.

- **DeviceRestController** creates a REST interface to the service so that some data is forwarded to the BUOS service via this interface. This class belongs to the “rest” package.
- **MSB Client** enables the BUOS to connect to the ESP. This and the other two classes below are the main components of the “msb” package.
- **MSBEventHandler** creates the events to be sent to other services via the ESP cloud platform.
- **MSBEventPublisher** creates the functions that receive the data from other services through the ESP cloud platform.

The next chapter introduces the algorithms and calculations used in the significant BUOS classes.

### 5.3.3 Service Algorithms and Calculations

This chapter describes the used algorithms and calculations in the service classes of the BUOS. The BUOS consists of three major classes in which the charging and discharging points of the AGVs are calculated. There are AvailabilityFinder, OptPointsCalculator, and FinalPointsCalculator.

In the AvailabilityFinder class, InfluxDB is called to read the availability data of the AGVs for the given time and company and AGV ID. This data is stored in an integer list so that it can be used later by FinalPointsCalculator.

OptPointsCalculator class creates a list of times when the AGV batteries should be discharged to cover the peak loads. To make this possible, energy consumption data is first subtracted from generated energy data and renewable energy sources and compared with the maximum permitted peak power for the manufacturing company. Then the time (15 minutes time interval) is stored in a list as the optimum time for the AGV battery to discharge.

$$P_{Production}(t) - P_{Renewable}(t) \geq P_{Peak} \rightarrow t_{opt} = t \ (2)$$

FinalPointsCalculator class determines the final charging and discharging times for the AGV batteries. First, the AGV states for the time interval are read from the InfluxDB. AGV states consist of 15 values (1: charging, 0: idle, and -1: discharging) for one optimum time point, which is determined in OptPointsCalculator. Next, it is compared to what kind of AGV states the optimum point has. If the AGV state is discharging, then it is left the same. For the AGV states with idle and charging, it is verified when the AGV state can be changed so that the peak load (energy consumption of the company) can be reduced.

$$if\ AGV_{state(t_{opt})} == -1 \rightarrow Do\ nothing\ (3)$$

$$if\ AGV_{state(t_{opt})} == 0 \rightarrow verifyStateChange\left(AGV_{state(t_{opt})}\right) (4)$$

$$if\ AGV_{state(t_{opt})} == 1 \rightarrow verifyStateChange\left(AGV_{state(t_{opt})}\right) (5)$$

During verifying the AGV state change probability, three conditions are examined. The first condition is to check that the SOC of the AGV batteries stays between the allowed ranges:

$$if(SOC_{AGV\_new}(t_{opt}) < SOC_{max})\ (6)$$

$$if(SOC_{AGV\_new}(t_{opt}) > SOC_{min})\ (7)$$

After that, it is calculated if the reduced grid charge for the time point is greater than the AGV degradation cost:

$$if\left(reduced\ grid\ charge(t_{opt}) > AGV\ degradation\ cost(t_{opt})\right)\ (8)$$

In the last condition, it is verified that the charging station should be available at the time point. The availability of the charging station can have two values (0: not available, 1: available).

$$if(CS\_availability(t_{opt}) == 1) \rightarrow changeState\left(AGV\_state(t_{opt})\right)\ (9)$$

After all conditions are verified, the AGV state is changed from 0 (idle) to -1 (discharging) or 1 (charging) to 0 (idle). After all AGV states for the determined optimum times are examined and changed, the overall cost savings for reducing the peak loads of the manufacturing company is calculated. The following formula shows the calculation of the cost savings in the BUOS for an AGV:

$$AGV\ cost\ savings = Reduced\ grid\ charge - AGV\ charging\ cost - AGV\ degradation\ cost \quad (10)$$

The reduced grid charge can be calculated with the multiplication of the power price and the power supplied by AGV batteries to the manufacturing company grid during peak periods:

$$Reduced\ grid\ charge = Peak\ power\ price\ x\ AGV\ battery\ supplied\ power \quad (11)$$

If AGV batteries are discharged during peak times, they should be charged during off-peak times. The following formula shows the charging cost of the AGV batteries:

$$AGV\ charging\ costs = Company\ electricity\ price\ x\ charged\ AGV\ battery\ capacity \quad (12)$$

The battery degradation of the AGVs' batteries is also considered in calculating the cost savings because the batteries should be additionally discharged during peak loads shaving, which causes aging of the batteries. First, the battery cost should be calculated by multiplying the AGV battery capacity with battery costs per kWh. Then, it is divided into the AGV battery cycles to calculate the degradation cost for one battery cycle. Last, the result should be multiplicated with SOC and divided by 100 to determine the degradation cost of the SOC amount that the AGV battery used to cover peak loads. The calculation of the battery degradation can be seen in the following formula:

$$AGV\ degredation\ cost = \frac{AGV\ battery\ capacity\ x\ battery\ costs\ per\ kWh\ x\ SOC}{100\ x\ AGV\ battery\ cycles} \quad (13)$$

After the cost savings for all AGVs are calculated, they are added to find out the overall cost savings for a manufacturing company with all AGVs:

$$Overall\ cost\ savings = \sum_{0}^{i\,=\,AGV\ amount} Cost\ savings(AGV_i) \quad (14)$$

The abbreviations used in this chapter are described in Table 5.1 below.

Table 5.1: Service Calculation Abbreviation Description

| Abbreviation | Description |
|---|---|
| **$AGV_{State}$** | State of an AGV battery (1: charging, 0: idle, and -1: discharging) |
| **CS_availability** | The availability of a charging station (0: not available, 1:available) |
| **i** | The AGV amount |
| **$P_{Peak}$** | Permitted maximum peak power of a manufacturing company |
| **$P_{Production}$** | The measured production power in a time point (in 15 minutes) |
| **$P_{Renewable}$** | The measured renewable power in a time point (in 15 minutes) |
| **SOC** | The current state of charge of an AGV battery |
| **$SoC_{AGV,new}$** | A new calculated state of charge of an AGV battery after discharging or charging an AGV battery |
| **$SOC_{max}$** | Permitted maximum state of charge of an AGV battery |
| **$SOC_{min}$** | Permitted minimum state of charge of an AGV battery |
| **t** | Time in one second |
| **$t_{opt}$** | Time in one second, at which an AGV battery can cover the peak load of a manufacturing company |

Table 5.2 shows the used parameters with their unit of measurement (UoM) to calculate the cost savings.

Table 5.2: Parameters to calculate the cost savings

| Parameters | UoM |
|---|---|
| **AGV battery capacity** | kWh |
| **AGV battery cycles** | - |
| **AGV battery supplied power** | kW |
| **Battery costs per kWh** | € |
| **Company electricity price** | ct/kWh |
| **Peak power price** | €/kW/a |
| **SOC** | % |

The following two chapters explain the data models of the DBs, such as MySQL, InfluxDB, and the MSB client components, such as MSB events and functions.

### 5.3.4 Service External Interfaces

This chapter visualizes the external interfaces of the BUOS software. The BUOS consists of three external interfaces (see Figure 5.5). The REST API of the BUOS enables other services to communicate to the MySQL DB of the BUOS. With the MSB client, the BUOS can communicate with other services in the company-side platform via MSB. The MSB client of the BUOS consists of events; with them, the BUOS can send data to other IT systems and functions, and through them, the BUOS receives data from other IT systems. The InfluxDB adapter of the BUOS generates the interface to the InfluxDB. Through this interface, the real-time data of the BUOS can be processed in the InfluxDB.

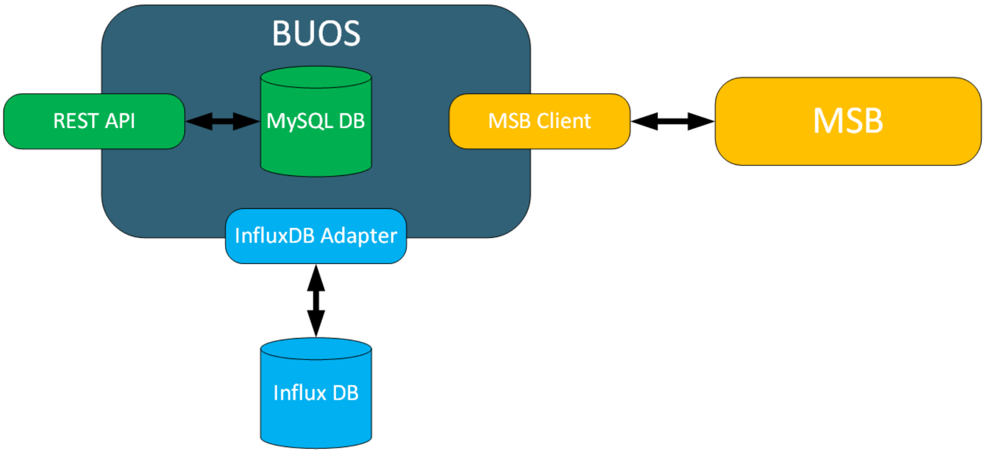



Figure 5.5: BUOS external interfaces

### 5.3.5 Service Data Models

The data models used in the BUOS and stored in MySQL and InfluxDB are presented and explained below.

Figure 5.6 depicts the BUOS MySQL class diagram. The BUOS consists of three main tables. They are AGV, Charging Station, and Power. In the AGV table, the AGV data of the companies are stored. The charging station table consists of the data of existing charging stations on the company's shop floor. The electricity costs, maximum allowed peak power, and its cost are saved in the power table.

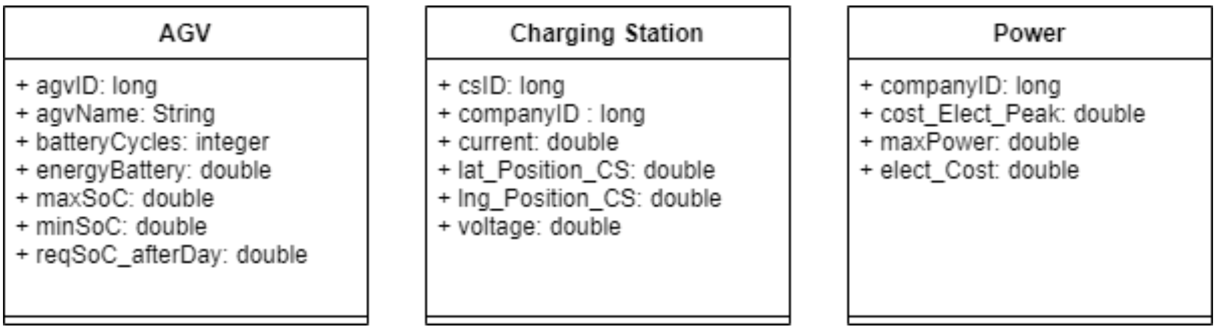



Figure 5.6: BUOS MySQL class diagram

Table 5.3 indicates the BUOS MySQL data model with the parameter descriptions. These parameters are saved and tagged with a company ID. The company ID, which is saved in MySQL, is unique for each company.

Table 5.3: BUOS MySQL data model

| Measurement | Parameter name | Description |
|---|---|---|
| **AGV** | agvID | AGV ID |
| | agvName | AGV name |
| | batteryCycles | Number of the battery cycles of an AGV battery |
| | energyBattery | The energy level of an AGV battery |
| | maxSoC | Defined maximum SOC limit for an AGV battery |
| | minSoC | Defined minimal SOC limit for an AGV battery |
| | reqSoC_afterDay | Required SOC level of an AGV battery at the end of the working day |
| **Charging Station** | csID | Charging station ID |
| | companyID | Company ID |
| | current | The current level of a charging station |
| | lat_Position_CS | Latitude position of a charging station |
| | lng_Position_CS | Longitude position of a charging station |
| | voltage | The voltage level of a charging station |
| **Power** | companyID | Company ID |
| | cost_Elect_Peak | Contracted electricity cost of a company during peak loads (peak electricity cost) |
| | elect_cost | Contracted electricity cost of a company |
| | maxPower | Defined the maximal power level of a company |

Table 5.4 shows the BUOS InfluxDB data model with explanations of the field values. The InfluxDB data of the BUOS is saved with a timestamp. Per second for one year, the parameters described below were stored in InfluxDB.

Table 5.4: BUOS InfluxDB data model

| Measurement | Field value | Description |
|---|---|---|
| **Power** | productionPowerData | Consumed power data of the manufacturing plants of a company |
| | renewablePowerData | Generated power data of the renewable resources of a company |
| | companyID | Manufacturing company ID |
| | time | Date and time |
| **Charging Station** | csID | Charging station ID |
| | csAvailability | Availability of a charging station |
| | time | Date and time |
| **AGV** | agvID | AGV ID |
| | velocityAGV | The velocity of an AGV |
| | agvLatPosition | Latitude position of an AGV |
| | agvLngPosition | Longitude position of an AGV |
| | socAGV | SOC of an AGV lithium battery |
| | agvAvailability | Availability of an AGV |
| | time | Date and time |

### 5.3.6 Service MSB Events and Functions

Below the MSB events and functions are described in more detail with their information data models.

**BUOS MSB events:**

- **SendFinalPoints:** The calculated final charging and discharging points (times) are sent to the AGVs.
- **Send FlexibilityEvent**: The bundled results from the BUOS (e.g., the total discharging capacity of the AGVs during peak loads in production) are offered as EFDM and sent to the EFMS via the company-side platform.

The information data model of the BUOS event “SendFinalPoints” is illustrated in Table 5.5.

Table 5.5: Information data model of the BUOS event “SendFinalPoints”

| Parameter name | Description |
|---|---|
| **finalPoints** | The final calculated charging and discharging points (times) for the AGV battery |
| **EVENT_NAME** | Name of the MSB event |
| **EVENT_DESCRIPTION** | Description of the MSB event |
| **EVENT_ID** | The ID of the MSB event |

Table 5.6, Table 5.7, and Table 5.8 display the information data model, which is used by the BUOS event “Send FlexibilityEvent” and defined in the papers (Bauernhansl et al. 2019, pp. 260–261) (Schott et al. 2019, pp. 5–19).

Table 5.6: Information data model of the BUOS event "Send FlexibilityEvent" part 1

| Measurement | Parameter name | Description |
|---|---|---|
| **FlexibilityEvent** | flexibility | Object to describe Flexibility class |
| | EVENT_NAME | Name of the MSB event |
| | EVENT_ DESCRIPTION | Description of the MSB event |
| | EVENT_ID | The ID of the MSB event |
| **Flexibility** | id | The ID of the flexibility measure |
| | flexibleLoads | Object to describe FlexibleLoad class |
| | storages | Object to describe Storage class |
| | dependencies | Object to describe Dependency class |
| **Flexible-Load** | flexibleLoadId | ID to uniquely identify a flexible load and address the corresponding device |
| | Activation-Gradient | Describes the performance gradient when the power is increased. |
| | costs | Includes all costs associated with using the flexible load, excluding electricity costs. |
| | Deactivation-Gradient | Analogous to the activation gradient for the final deactivation period |
| | Modulation-Gradients | Analogous to the activation gradient for the modulation periods |
| | Modulation-Number | Indicates the number of modulations (changes in power state) that can occur during an application of the process. |
| | Reaction-Duration | Describes the period until the power starts to fluctuate. |
| | Regeneration-Duration | Describes how long the same flexibility may not be re-drawn after the end of the holding duration of a flexibility draw. |
| | usageNumber | Specifies how often the flexibility can be used at a minimum and maximum in an interval. |
| | powerStates | Object to describe PowerState class |
| | validity | Object to describe Validity class |

Table 5.7: Information data model of the BUOS event "Send FlexibilityEvent" part 2

| Measurement | Parameter name | Description |
|---|---|---|
| **Power-State** | value | Describes possible performance levels through a set of intervals. Each interval can be either continuous or discrete. A minimum and maximum sequence and a discrete interval by a non-empty sequence of functions define a constant interval. |
| | Holding-Duration | Specifies how long the flexibility can be used at a minimum and maximum in an interval. |
| **Validity** | start | Specifies the start time of a period in which the flexibility is allowed to be utilized |
| | end | Specifies the end time of a period in which the flexibility is allowed to be utilized |
| | Temporal-Type | The parts ("start," "total," "end") of the validity |
| **Storage** | storageId | Used for the unique identification of memories and enables their unique referencing within single flexibility. |
| | costs | Includes all costs associated with using the flexible load, excluding electricity costs. |
| | drain | An unchangeable load that must be served during production |
| | energyLoss | Describes the demand for useable energy for each time within the validity period. |
| | initialEnergy-Content | Object to describe EnergyContent class, initial energy content from AGV batteries |
| | suppliers | Object to describe Supplier class |
| | targetEnergy-Content | Object to describe EnergyContent class targeted energy content from AGV batteries. Target energy content of an AGV, which should be fully charged at the beginning of a production day (shift). |
| | Usable-Capacity | Describes the usable capacity of the corresponding storage for the energy flexibility measures |
| **Energy-Content** | value | Describes the SOC level of the corresponding storage of flexibility |
| | time | Timestamp for the Energy content of the storage |

Table 5.8: Information data model of the BUOS event “Send FlexibilityEvent” part 3

| Measurement | Parameter name | Description |
|---|---|---|
| **Supplier** | Flexible-LoadId | ID to uniquely identify a flexible load and address the corresponding device |
| **Dependency** | conversion-Efficiency | A set of flexible loads which supply the storage. With each supplier, there comes an additional parameter, namely conversion efficiency. |
| | Target-Flexible-Load | Object to describe FlexibleLoadReference class, the ID of the flexible load which is affected by the trigger flexible load. |
| | logicalType | Object to describe LogicalType class |
| | applicability-Duration | After using the trigger flexible load, the period for which the flexible target load must be activated at least once (“implies”) resp. not at all (“excludes”). |
| | applicability-Conditions | Object to describe Condition class; Additional conditions must be satisfied, and the dependency must be fulfilled. |
| **FlexibleLoad-Reference** | Temporal-Type | The parts (“start,” “total,” “end”) of the trigger flexible load (first component) and the flexible target load (second component) are affected by the dependency. |
| | Flexible-LoadId | ID to uniquely identify a flexible load and address the corresponding device |
| **LogicalType** | - | Enum value (IMPLIES, EXCLUDES) |
| **Condition** | formulaLeft | Additional conditions must be satisfied such that the dependency is regarded to be fulfilled. |
| | Formula-Right | Additional conditions must be satisfied such that the dependency is regarded to be fulfilled. |
| | comparator | Object to describe ComparisonType class |
| **Comparison-Type** | - | Enum value (EQUALS, LESS, LESSEQUAL, GREATER, GREATEREQUAL) |

**BUOS MSB functions:**

- **getData**: The required data, such as agvIDs and companyID for the final charging and discharging points calculation of the AGV batteries, is transferred by the AGV to the BUOS.

Table 5.9 shows the transferred data to the BUOS “getData” function.

Table 5.9: Information data model of the BUOS function getData

| Parameter name | Description |
|---|---|
| **agvIDs** | AGV IDs |
| **companyID** | Company ID |

- **getConfirmation**: The confirmation data is sent by the EFMS to the BUOS so that the calculated final points (scheduling data) can be sent to the corresponding AGV to enable energy flexibility.

Table 5.10 shows the confirmation data of the EFMS that sends it to the BUOS.

Table 5.10: Information data model of the BUOS function getConfirmation

| Parameter name | Description |
|---|---|
| **EFDM** | EFDM equals to FlexibilityEvent, which is described above. |
| **confirmation** | It is a boolean value, which starts the energy flexibility process. |

## 5.4 Service Working Procedure

This chapter explains the working procedure of the BUOS software. This procedure is illustrated in four divided swim lanes. The swim lanes consist of the software services AGV software, BUOS, and EFMS. The functional components (classes) of the BUOS are also shown in the swim lanes.

The first part of the swim lane (see Figure 5.7, Figure 5.8, and Figure 5.9) describes the working procedure from the beginning until AvailabilityFinder requests AGV availability (state) points. The working procedure begins with the software service AGV software, placed and runs in an AGV. This service sends the corresponding AGV IDs and company ID of the AGVs to the BUOS via MSB.

In the MSBEventHandler class of the BUOS, it is first verified whether it is a new task that arrived from the AGVs. If it is not a new task, the program waits for the points calculation process to be done. If a new task is achieved, AGV IDs and company ID are saved in the BUOS. After that, in a for-loop, MSBEventHandler communicates to the AlgorithmManager to request the final charging and discharging points for the corresponding AGV IDs. AlgorithmManager redirects this request to the FinalPointsCalculator class, where final charging and discharging points are calculated.

First, FinalPointsCalculator requests peak time points for the time period between the start and end times of the corresponding AGV from OptPointsCalculator. The renewable and production data from InfluxDB are required to calculate these points. After OptPointsCalculator sends the request to the InfluxDBAdapter class. InfluxDBAdapter finds requested data and sends it back to OptPointsCalculator.

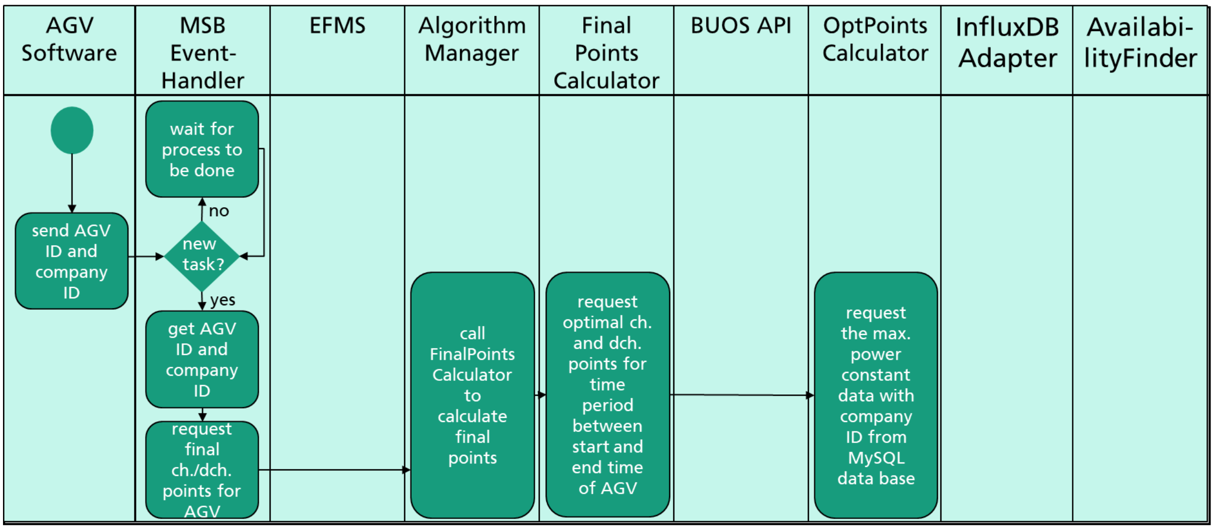



Figure 5.7: Service working procedure - part 1.1

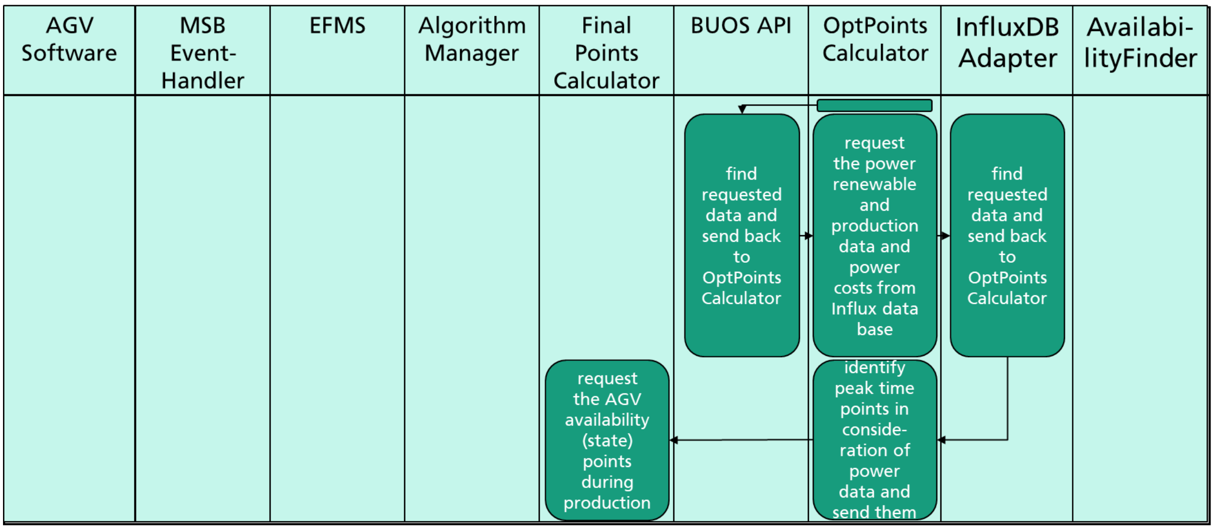



Figure 5.8: Service working procedure - part 1.2

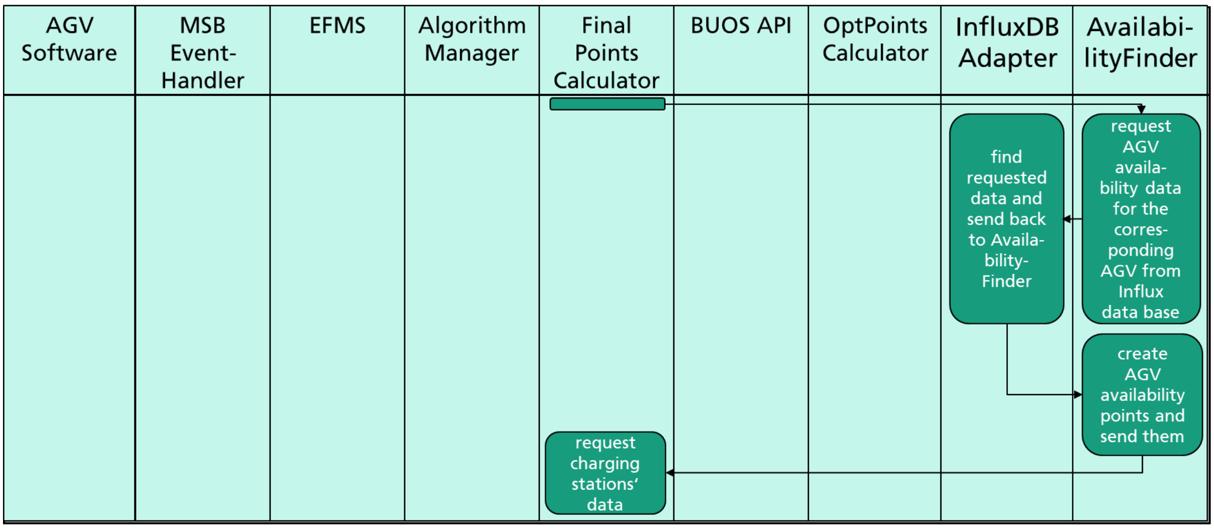



Figure 5.9: Service working procedure - part 1.3

Last, in consideration of the power data, optimal peak time points are calculated, and OptPointsCalculator sends them back to FinalPointsCalculator. After that, the AGV availability (state) points during the production period are requested from the AvailabilityFinder class.

The second part of the swim lane (see Figure 5.10 and Figure 5.11) shows the working procedure from the time period, in that the AGV availability (state) points are requested from AvailabilityFinder until the AGV availability (state) points for the peak time are created.

The InfluxDBAdapter finds the requested availability points and sends them back to AvailabilityFinder, where AGV availability (state) points are created for FinalPointsCalculator. After FinalPointsCalculator receives the AGV availability data, the charging stations' data is requested from InfluxDB. Then, the required data from different DBs are requested to validate the first (checkSoC), second (checkElectCost), and third (checkCSAvailability) conditions.

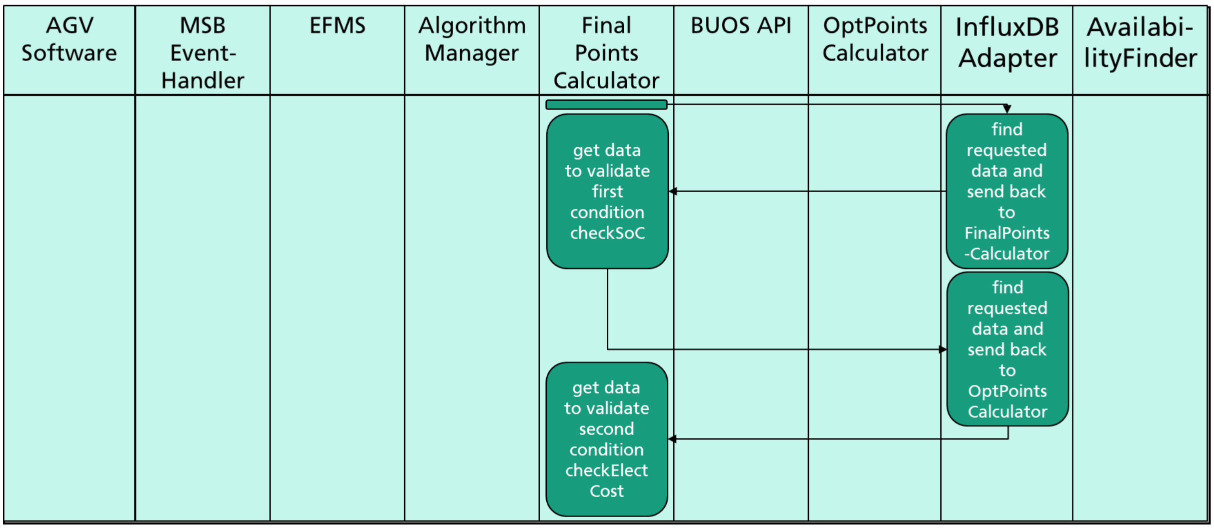



Figure 5.10: Service working procedure - part 2.1

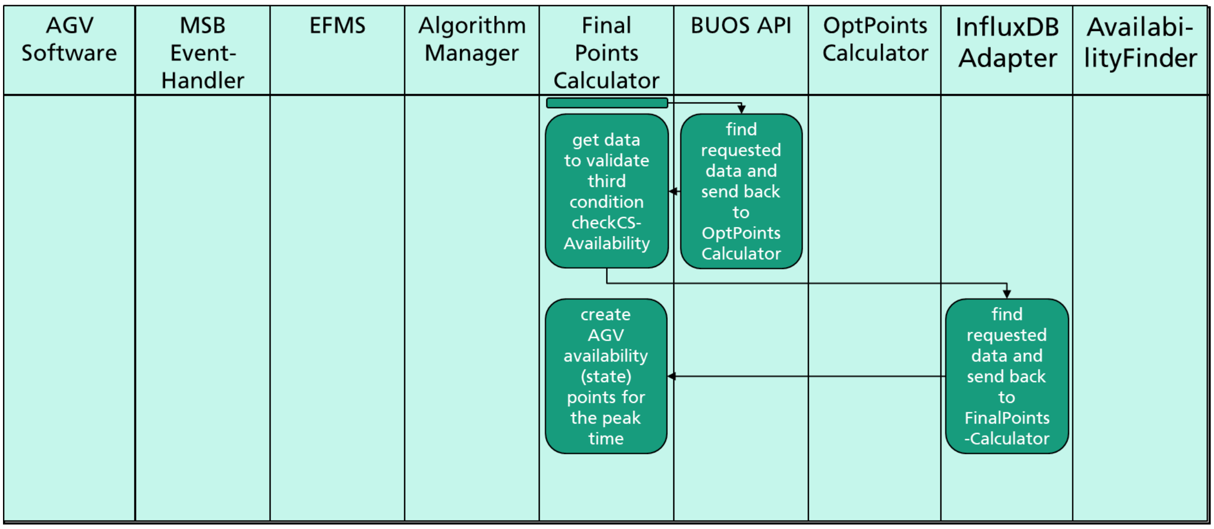



Figure 5.11: Service working procedure - part 2.2

The third part of the swim lane (see Figure *5.12*, Figure 5.13, Figure 5.14, Figure 5.15, and Figure 5.16) explains the working procedure from the time period. Different point state cases are shown, and the chosen point is validated considering three conditions.

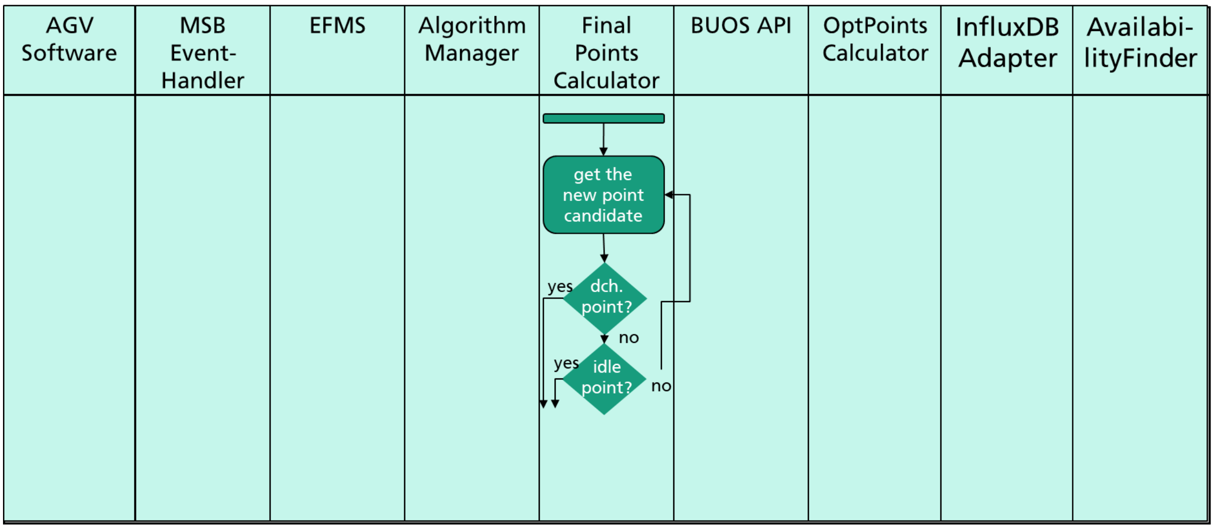



Figure 5.12: Service working procedure - part 3.1

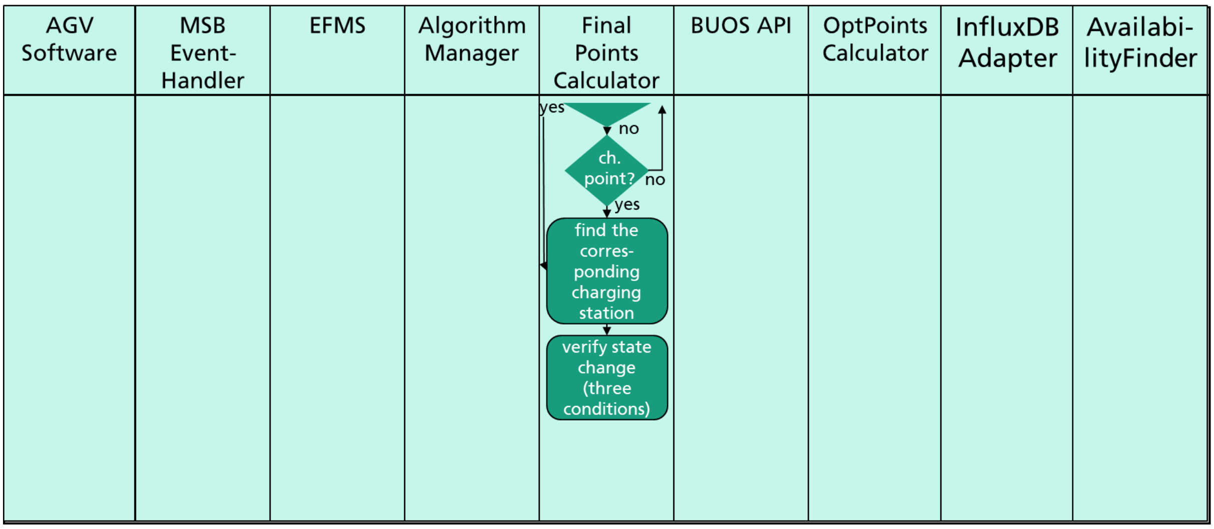



Figure 5.13: Service working procedure - part 3.2

First, it is identified when the point is a discharging (dch.), idle, or charging (ch.) point. Then the corresponding (nearest) charging station at the time point is found. After that, three conditions are verified. As a first condition, it is checked if the AGV SOC level lies between the defined minimal and maximal SOC level. If it is not possible, a new charging point is being searched. Then, it is verified if the degradation costs of the AGV during this procedure are lower than saved energy costs, where the AGV battery covers the peak loads during discharging point time. If it is the case, the last condition is checked if the corresponding charging station, where the AGV battery can be charged or discharged, is free. After all conditions are checked successfully, the point candidate is saved as a discharging, idle, or charging point. If one of the conditions is not fulfilled, then the next point candidate is taken to examine all conditions described above.

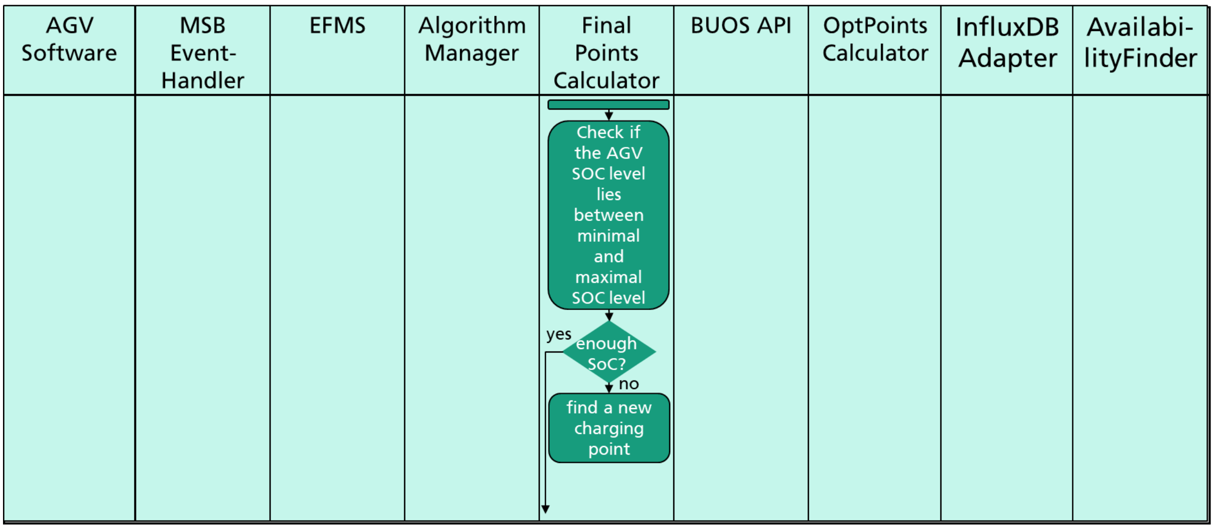



Figure 5.14: Service working procedure - part 3.3

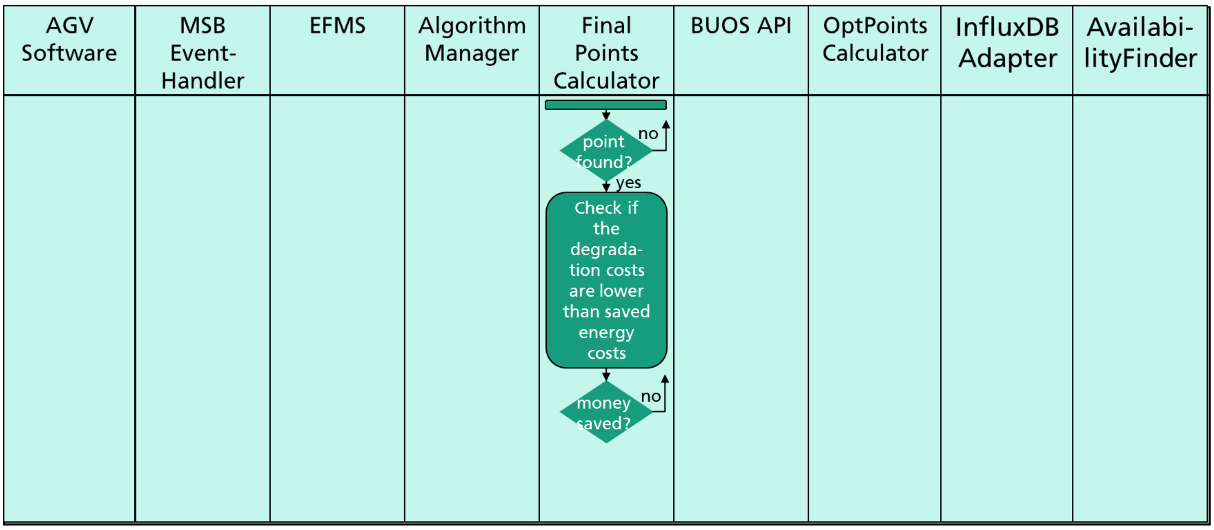



Figure 5.15: Service working procedure - part 3.4

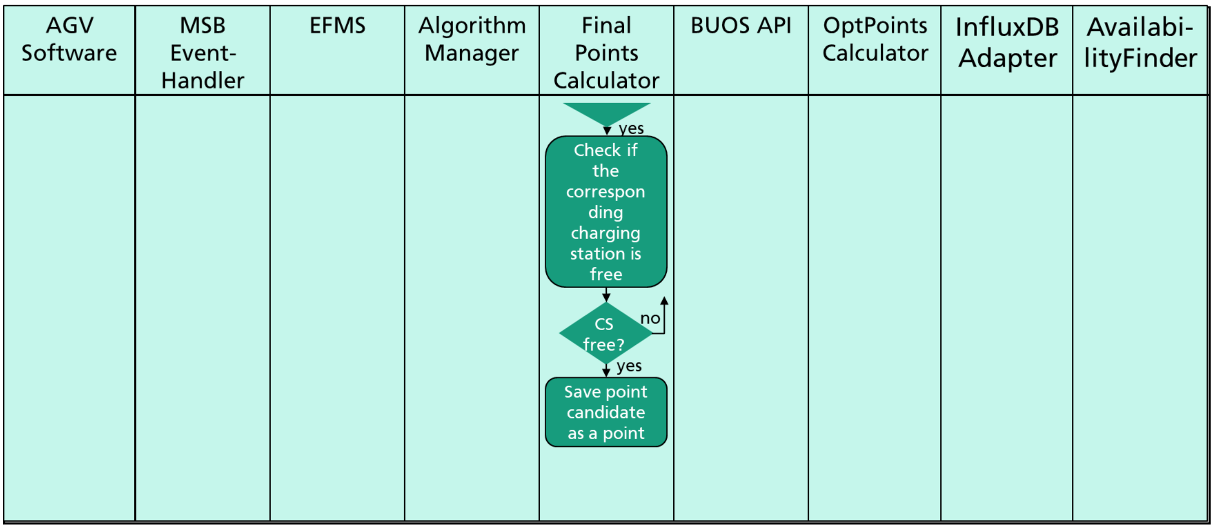



Figure 5.16: Service working procedure - part 3.5

Figure 5.17 and Figure 5.18 display the last part of the service working procedure. After a final list of the points is created, the following data, such as the charging station availability list, current SOC AGV list, production data, and AGV availability points, should be adjusted. Therefore, different lists are created for this data to adjust later. Then the cost savings, which are saved with this service during peak load times for the affiliated company, are calculated.

As a next step, an EFDM is created in MSBEventHandler with the help of the calculated cost savings and final points. This EFDM is sent via MSB to the EFMS. After a user accepts the offer in EFMS, an acceptance confirmation is sent back to the BUOS (to the MSBEventHandler) via MSB. For the BUOS, the created lists are used to adjust the charging station's availability list, current SOC AGV list, production data, and AGV availability points in InfluxDB. InfluxDBAdapter performs this task and changes data in InfluxDB for the following AGV charging and discharging points calculations. After it is done, the final points (charging, idle and discharging points) are sent to the AGV software of the corresponding AGV. Last, the next AGV in the for-loop enables further peak-shaving for the related company.

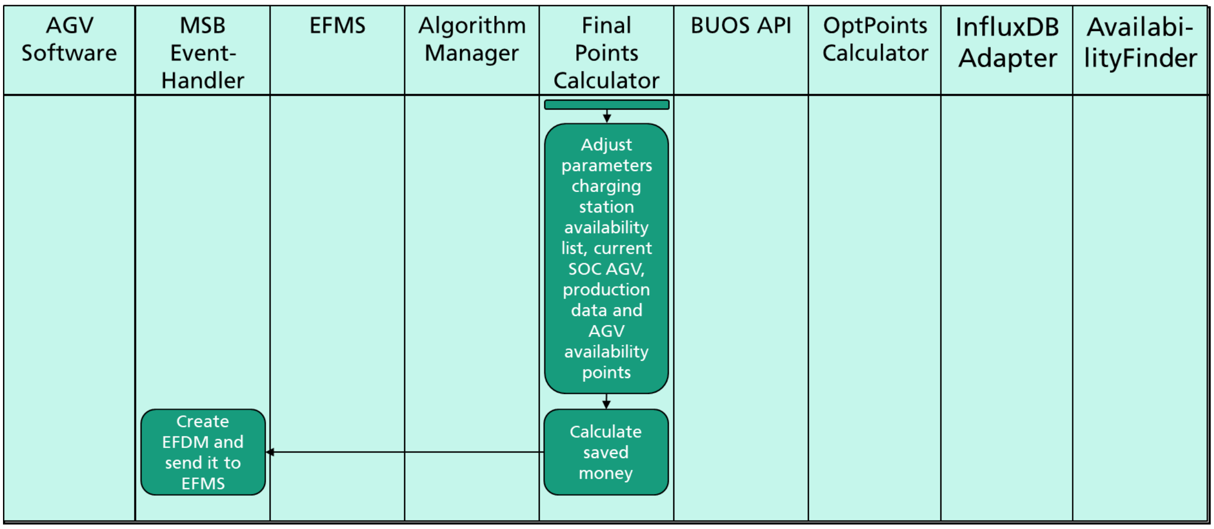



Figure 5.17: Service working procedure - part 4.1

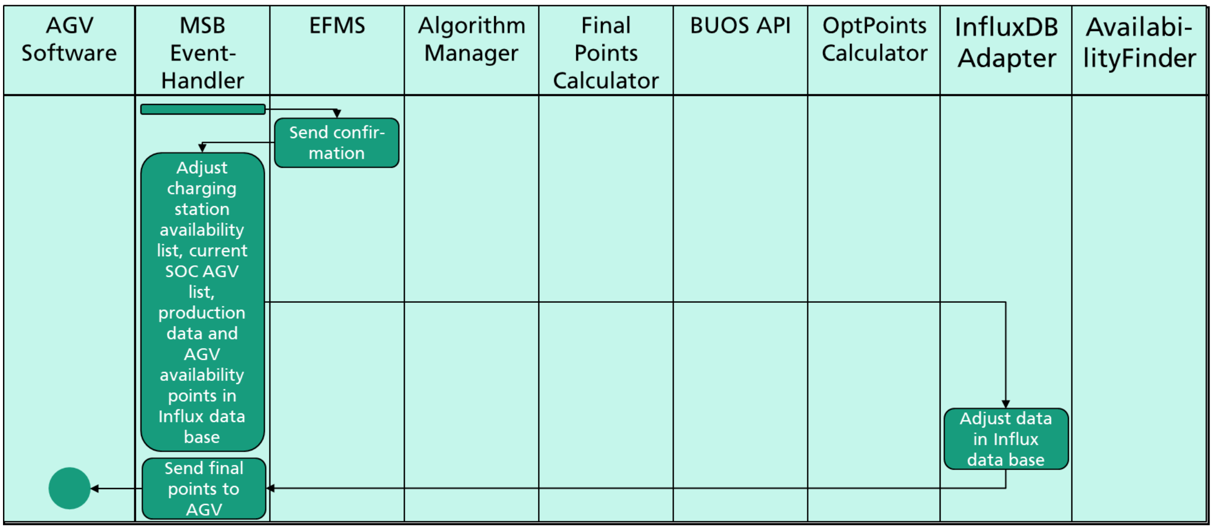



Figure 5.18: Service working procedure - part 4.2

## 5.5 Execution Tests

Testing is a significant factor in any software development project. All developed codes should be tested before launching. Therefore, first, the term software testing and its levels are described in this chapter. Secondly, the chosen testing level and its testing frameworks are presented. Last, the written tests for the BUOS are shown, and the test results of the BUOS software are introduced.

### 5.5.1 Software Testing and Its Levels

“Software testing is a process, or a series of processes, designed to ensure computer code does what it was designed to do and does not do anything unintended. Software should be predictable and consistent, offering no surprises to users.” (Myers et al. 2004, p. 8). Software testing includes four levels, which are presented below.

#### 5.5.1.1 Unit Testing

Unit testing is a software testing method that tests single units of source code to verify that they are operational (Huizinga et al. 2007, p. 75).

Unit tests (UT)s are performed during the early stage of the software-programming life cycle. This testing method's advantage is reducing software development risks, time, and costs.

The UTs have the following advantages (Boog 2020):

- The UT shows bugs in the written code before the software has an integration test.
- If the programmer adjusts the code, the UT illustrates the problems caused by the code adjustment. It helps the programmer see the issues for each code unit.
- UT forces the programmer to write better code and design it.
- UT reduces the overall cost and time for writing a code.
- UT creates documentation, which is helpful for the programmer to understand the problems in a code. It simplifies the debugging process.

Besides the advantages, the UTs cause the programmer some disadvantages. These are (Boog 2020):

- To perform UTs, the programmer should write more code. It means that the amount of code that should be written will increase. The amount of code depends on the complexity of the code. If a code has many classes, the number of UTs increases linearly.

- The UTs are not suitable for GUI testing. They are used to test the logic of implementation. The BUOS does not consist of a GUI. Therefore, this advantage does not valid for the BUOS.
- The UTs cannot find all errors in a code. The performance of the UTs depends on the programmer who writes the UTs.
- If the programmer in a code adds a new class, the UTs should be written to test new functionalities of the new class. This takes extra time for the programmer.

#### 5.5.1.2 Integration Testing

Integration tests investigate the functionality of interdependent components. The test focuses on the interaction between the modules and interfaces of the components (Leung et al. 1990, p. 290).

#### 5.5.1.3 System Testing

The system testing tests check the requirements of a fully developed system with all its components (IEEE Computer Society 1990, p. 197). Suppose a GUI, such as a login GUI, is considered a system. In that case, the functionalities of the components of this system, such as creating, editing, or deleting a user and the login or logoff process, are examined during the system testing.

#### 5.5.1.4 Acceptance Testing

In software engineering, user acceptance tests are the tests of whether the software works as intended from the user's point of view and whether the user accepts the software (Cimperman 2006, 6-32). This testing aims to examine whether the tested system fulfills all requirements of the end-user of the software.

#### 5.5.1.5 Software Testing Selection

Although UT has some disadvantages, the bullet points of the advantages clarify that unit testing is essential to test the software. The software should be tested in small units, and this testing method helps the programmer find problems in the code faster.

Even though the programmer has to write more code because of UTs and loses some time, the code is tested in more detail, and the errors are identified faster. Therefore, it is decided by the author of this thesis to use the minor software testing method, “unit testing”. After the execution of the UTs successfully, the integration and system tests of the BUOS are also performed. The acceptance tests are not a part of this work. They are usually done by the customer or the user at the end. The next chapter introduces the testing method “unit testing” frameworks.

Few programming languages, such as Python, Java, Matlab, etc., support unit testing. The BUOS is developed with the programming language Java. Therefore, only the unit testing frameworks of Java are considered in this chapter. There are more than 40 existing unit-testing frameworks, which various programmers developed. Only the more experienced unit testing Java frameworks are introduced in this chapter. JUnit and TestNG are modern and most-used frameworks for unit testing in the Java ecosystem (Baeldung 2019). Therefore, both frameworks are compared. A comparison is performed by (Baeldung 2019) to evaluate both tools. The last version of the JUnit framework, JUnit5, is considered in this comparison. According to (Baeldung 2019), the comparison results are presented in Table 5.11.

Table 5.11: Comparison of JUnit and TestNG testing frameworks

| | Frameworks | |
|---|---|---|
| **Challenges** | **JUnit** | **TestNG** |
| **Test Setup** | The JUnit framework can perform the initialization and cleanup at two levels (before and after each method and class). | The TestNG also offers initialization and cleanup at the method and class level. |
| **Ignoring Tests** | Both frameworks support ignoring test cases. | |
| **Running Tests Together** | Both frameworks support running tests together as a collection. | |
| **Testing Exceptions** | The feature for testing for exceptions using annotations is supported in both frameworks. | |
| **Parameterized Tests** | JUnit provides the advantage of test methods to consume data arguments directly from the configured source. | Tests can be parametrized by using some annotations in the TestNG framework. |
| **Test Timeout** | Timed-out tests test whether a code's execution is done within a specified period. Both frameworks provide timed out tests. | |
| **Dependent Tests** | In dependent tests, first, the initial test is performed. If it is failed, all its subsequent tests will be skipped. | |
| | JUnit does not support dependent tests. | TestNG provides dependent tests. |
| **Order of Test Execution** | Both frameworks support having control in the order of test method execution. | |
| **Custom Test Name** | JUnit offers a unique feature so that the custom descriptive names for class and test methods can be defined. This feature helps the programmer to understand test results easier. | TestNG does not provide customizing test names. |

As seen in the upper table, both frameworks consist of similar features. However, the feature custom test name is a vital feature relevant for the testing of BUOS. No dependent tests are planned for the BUOS. Therefore, it is decided by the author of this work to use the JUnit framework as a unit-testing framework. The next chapter presents the written JUnit tests for BUOS and their results.

### 5.5.2 BUOS Junit Tests and Results

In this chapter, the BUOS JUnit tests and their results are described. Four JUnit tests are written for unit testing of the BUOS. These are

- AvailabilityFinderTest
- FinalPointsCalculatorTest
- InfluxDBManagerTest
- OptPointsCalculatorTest

Figure B.*1* depicts the results of the unit tests for the AvailabilityFinder class of the BUOS. Two functionalities of the class were examined. First, it is tested whether the granularity adjustment works in the class. Then it is checked whether the available points were found correctly.

With the help of the FinalPointsCalculator JUnit tests (see Figure B.*2*), fourteen internal functions of the class FinalPointsCalculator are checked. According to the test results, all components of this class ran without error.

InfluxDBManager unit tests, depicted in Figure B.*3*, are designed to check the connectivity of the BUOS to InfluxDB. The results show that the BUOS communicates with InfluxDB without failure and can both read data from and write data to this DB.

Two functionalities were tested with the OptPointsCalculator unit tests. As a result, it is illustrated that the class OptPointsCalculator performs appropriately (see Figure B.*4*).

According to the test results, it can be stated that the BUOS works appropriately without errors. After the unit tests are executed successfully, in the following chapter, integration tests are conducted to test the interfaces of the different components (modules) of the BUOS.

### 5.5.3 Integration Tests and Results

The communication between three packages (modules) of BUOS is tested using integration tests. The classes of the “core” package communicate with the “api” package so that the data from the MySQL DB can be used and processed. The same communication principle applies between the “influxdb.adapter” and “core” packages. This chapter uses some integration tests without mocking the DBs to test the two above-mentioned use cases. According to the results, the tests are conducted successfully.

### 5.5.4 System Tests and Results

The interfaces of the overall system BUOS are tested in this chapter. The BUOS consists of a REST interface and InfluxDB interface, which provide whether to save new data or to read requested data from both DBs for the BUOS, and MSB interfaces, where it communicates to other software services via MSB in the company-side platform.

To examine the InfluxDB interface, the unit tests of InfluxDBManager, explained in the previous chapter, are used without mocking the InfluxDB. According to the tests’ results, the BUOS can successfully read and write data in InfluxDB. To test the REST interface of the BUOS, some REST calls are created with the help of the API development software Postman (Postman 2021). Three different REST methods are applied in this test. They are

- GET: This method aims to read the requested data from a DB
- PUT: This method prompts a request for a change in a DB
- POST: The POST method creates a new dataset in a DB

Figure B.*5* indicates the test results of the BUOS REST interface with the GET method. It can be seen that the REST interface of the BUOS works appropriately.

The BUOS REST interface test with the PUT method is applied to examine whether the dataset in the DB will be updated with the submitted data. Figure B.*6* shows that the test is performed successfully.

Figure B.*7* indicates the successfully performing of the BUOS REST interface test with the POST method. At the end of the test, a new dataset of AGV is created in the DB.

Next, the MSB events (SendFinalPoints, FlexibilityEvent) and functions (getData, getConfirmation) are tested with the help of integration flows of the MSB in this chapter. Integration flows enable mapping software services in MSB together so that they can exchange data. Below (see Figure 5.19 and Figure 5.20), two integration flows are displayed to test the BUOS events and functions mentioned above.

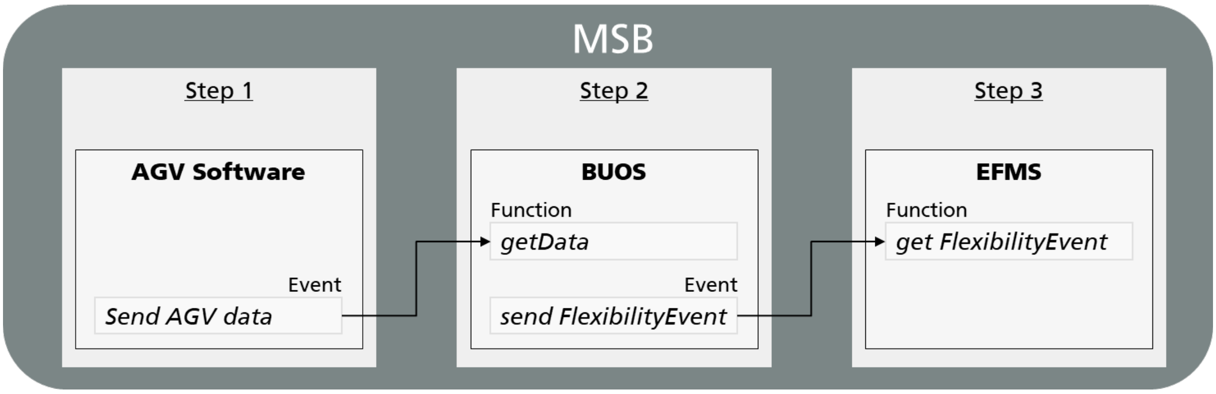



Figure 5.19: MSB test integration flow 1

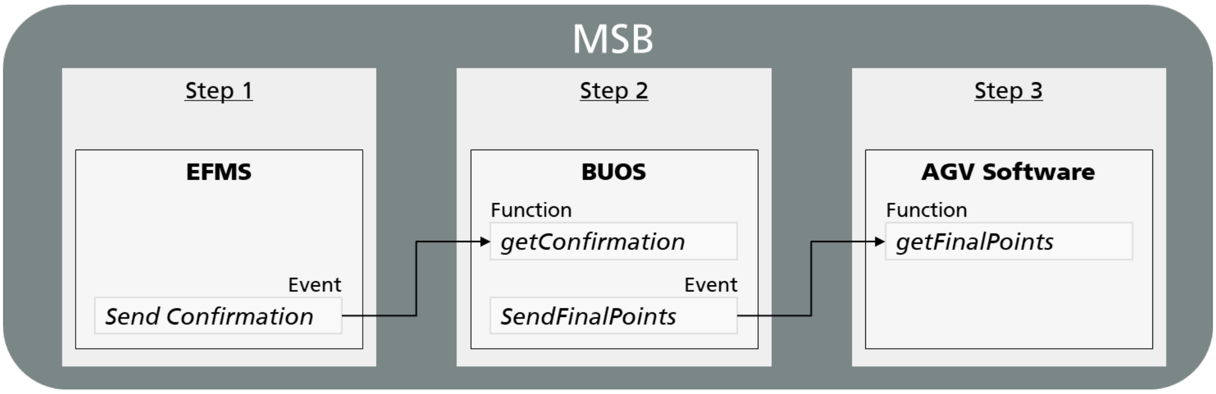



Figure 5.20: MSB test integration flow 2

According to the test results, it is determined that the BUOS MSB interface functions without error. The BUOS is deployed as a service in the next chapter to be used in different use case scenarios.

## 5.6 Service Deployment

This chapter describes the BUOS deployment in the company-side platform. As depicted in Figure 5.21, the software services are hosted in the company-side cloud platform. Cloud systems can be used for planning, ongoing process interaction, or even executing automated decisions and sending corresponding control signals to the production plants. In this way, production equipment is synced, and times of insufficient utilization are reduced when they work together in a process (Fallenbeck et al. 2017, p. 141). Therefore, this technology is integrated into this dissertation so that all software services, such as BUOS, the InfluxDB, and MSB, later used to validate the validation results of the BUOS deployment in manufacturing companies, are hosted in the company-side cloud platform.

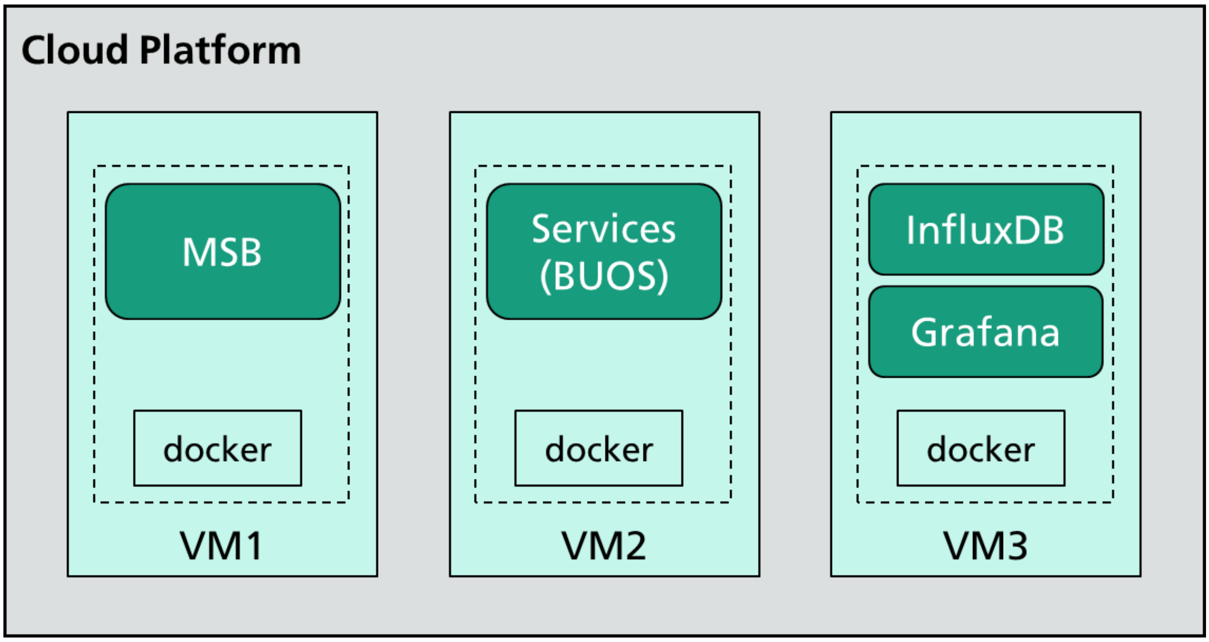



Figure 5.21: Hosting services and databases in the company-side cloud platform

The cloud platform used in this dissertation consists of various virtual machines (VM). The VMs are software programs that perform like a real computer by emulating a computer hardware system. The benefits of utilizing VMs are stated as VMs “are now seen as cost-effective techniques for organizing computer systems resources to provide extraordinary system flexibility and support for certain unique applications” (Goldberg 1974, p. 34). The services and DBs in this dissertation are divided into three VMs.

Service segregation in different VMs allows flexibility and quick integration into the company-side platform. It also enables the user to categorize instances with other jobs in the company-side platform. This VM separation enables IT administrators to quickly locate and pick the right VM for their tasks in case of issues and related maintenance tasks. Moreover, VM separation also offers the added benefit that service development and testing can continue. For example, another VM remains in the process of being configured by an IT admin. Both operations can run parallel without any problems and are not disturbed by the other.

Software services are deployed using Docker in the company-side cloud platform, which eases deployment complexity, improves productivity, and reduces time wasted on bug fixing. Docker is an open-source software project that helps automate software service deployment in the form of portable, standalone containers hosted in a cloud platform or on-premises (Microsoft 2021). Execution via Docker containers provides a fast startup of software services for code customizations and a consistent environment isolated from other software services. No matter where the software service is deployed, everything remains consistent, resulting in tremendous productivity: less debugging and more time rolling out new features.

## 5.7 Benefits of the Service

Arising benefits and potentials of using the BUOS service for manufacturing companies, which enable to use AGVs in manufacturing plants as energy stores, are described in this chapter.

The study by (BIS Research 2022) reveals that the performance and production of electrically powered AGVs will increase in the next three years. This study also predicts that there will be two times more AGVs with batteries in 2025 than 2020. This high number of AGVs provides a large battery capacity that can be used for peak load reduction in manufacturing companies. Moreover, in the study, 78 % of German companies stated that AGV usage in manufacturing plants is relevant to them. They are also dedicated to investing in developing planned energy flexibility measures (Bundesvereinigung Logistik 2018). The study Zimmermann et al. (2019, p. 38) shows that 17 % of the study participating companies are interested in optimizing energy procurement, such as grid fee reduction with peak shaving. According to 64 % of companies, their employees are actively involved in energy storage integration (Zimmermann et al. 2019, p. 76). It indicates that energy storage integration is essential for the companies, and the BUOS offers a significant potential to achieve their energy flexibility measures' targets.

The benefits of the BUOS service are:

- The energy flexibility realizes electricity cost savings in the company that the BUOS creates with the AGV batteries.
- The BUOS is a generic service for all AGV battery charging methods and schemes.
- The planned routes, the availability of AGVs, and the scheduling of production machines remain the same and are not affected or changed by this approach.

Overall benefits for the companies are also described in the following bullet points:

- With this concept of using AGV batteries as energy storage, companies do not have additional costs for new stationary batteries, battery maintenance, and charging stations. The batteries are already available in AGVs.
- Already operating charging stations can be used for peak-reducing purposes and power supply for the batteries to enable AGVs to perform their tasks in manufacturing.
- Employees in companies are already available for AGV maintenance tasks.

The companies define the additional space problem as one of the challenges of energy storage integration for stationary batteries (Zimmermann et al. 2019, p. 79). AGV batteries do not require additional space in the company, such as stationary batteries. The costs for extra space can be saved.

# 6 Use Case Based Validation

The validation results of the BUOS are illustrated using the sensitivity analysis validation method in this chapter. First, the use case scenarios of different manufacturing companies are described. Then the selected validation method sensitivity analysis is introduced. Last, the use case scenarios of various manufacturing companies are validated, and validation results are presented.

## 6.1 Use Case Scenarios

This chapter introduces three different use case scenarios (chemicals manufacturing use case (CMUC), plastic manufacturing use case (PMUC), and battery manufacturing use case (BMUC)) of the manufacturing companies. The BUOS calculates the cost savings for other companies in the use case scenarios.

The use case scenarios consist of the following subchapters:

- Company introduction: Both general and production-specific information from the selected company is presented.
- Simulation concept: The simulation concept for the logistic processes of the selected company is introduced.
- Simulation model description: The developed simulation model with the Plant Simulation for the selected company is described.
- Simulation model results: The results of the developed simulation model are shown in this chapter.

### 6.1.1 Chemicals Manufacturing Scenario

#### 6.1.1.1 Company Introduction

The company from the first use case scenario for which the simulation was developed is a chemicals manufacturer in the synthetic leather and textile coating industries. The company's factory is 4000 m$^2$ and consists of a warehouse and two production lines. The company's warehouse is located between two production lines (with a diameter of 30 meters). Between 70 and 100 tons of products are transported daily from the warehouse to the production lines. Two employees work three shifts daily in the company, and one team member transports a barrel with a forklift truck during one trip. With the help of this information, the concept's assumptions are described in the next chapter. The energy consumption data from the company of this use case is anonymized, illustrated in Figure 6.1. The red line shows the company's agreed maximal power (off-peak limit). Above the line, the peak energy loads of the company are indicated.

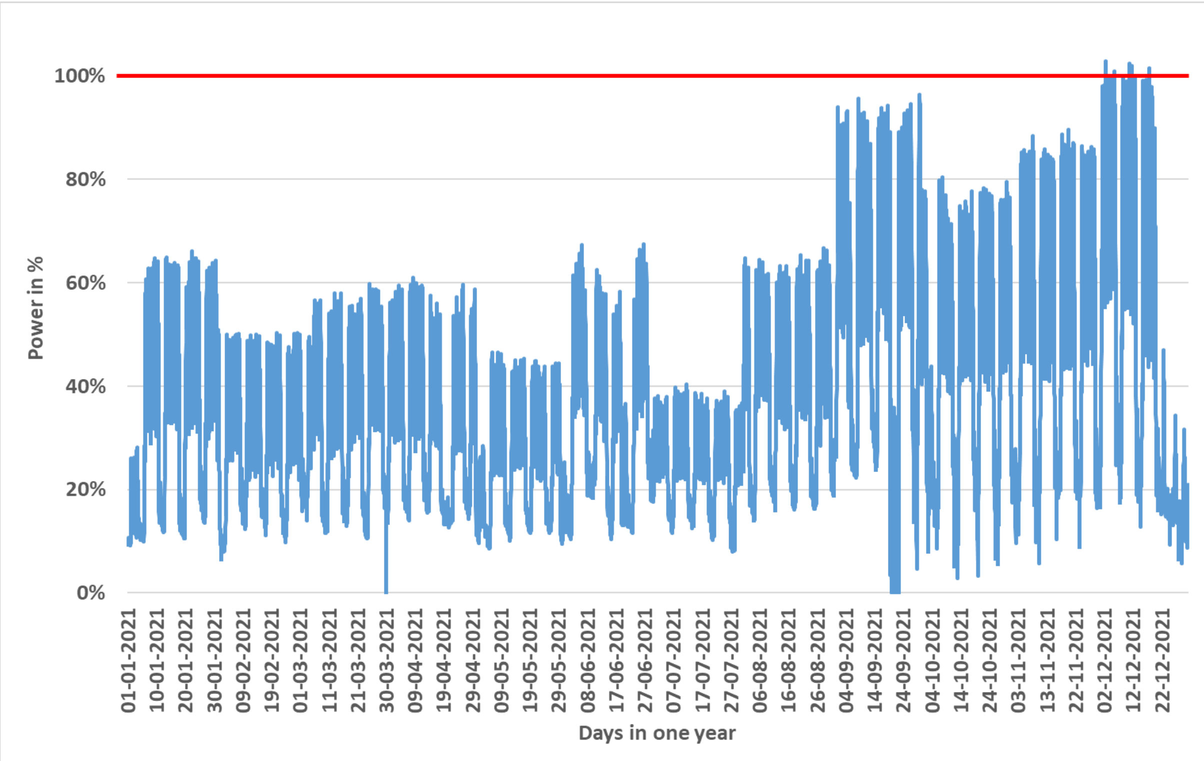



Figure 6.1: Chemicals manufacturing company - energy consumption data

#### 6.1.1.2 Simulation Concept

The simulation model should be developed with the AGV operation. The following assumptions in the simulation model are made for the logistics processes of the company to realize a realistic simulation:

- The simulation duration is set to 1-year simulation time from 01.01.2021 to 31.12.2021. To calculate how many peak loads can be covered with AGV batteries, AGV data for one year should be generated.
- The transport processes of two products (chemicals) are considered.
- The interval of the production orders (min. in 3 minutes and max. in 27 minutes) is calculated for one year per day using the energy consumption data set in the simulation.
- An AGV has an average speed of 1 m/s (approx. 4 km/h).
- The SOC limits of the AGV are predefined (20-90 % for the lithium battery saving). AGV shall drive to the charging station if the lower SOC limit is exceeded.
- All AGVs have an initial value of 50 % for the battery SOC.
- One AGV garage is located in the factory layout and consists of two AGVs. No employees are used for intralogistics. Instead, the AGVs have performed the intralogistics tasks.
- AGVs can transport the products to both production lines.
- AGVs should work 24 hours per day.
- Two charging stations are simulated so that AGV batteries are charged.

The data from KUKA KMP 1500 AGV (KUKA AG 2016) is used as the AGV data to generate a realistic simulation model. It is shown in Table 6.1.

Table 6.1: KUKA AGV data

| Feature | Value |
|---|---|
| **AGV battery charging current** | 52 A |
| **AGV battery charging voltage** | 96 V |
| **AGV battery capacity energy** | 9,984 Wh (extended battery version) |
| **AGV battery charging time** | 2 hours (up to 100 %) |
| **AGV driving consumption** | 13 A (min. 8 hours) |

After the assumptions are determined, the simulation model is developed. The next chapter presents the model description.

#### 6.1.1.3 Simulation Model Description

The decision was to use the Tecnomatix Plant Simulation simulator (SimPlan AG 2021) because it offers a large selection of objects from the production process and already existing models with battery-powered AGVs. Furthermore, the simulation can be adapted to the case study using the programs written in the SimTalk programming language.

The simulation model (see Figure 6.2) uses Steffen Bangsow's training example, which includes AGVs with tracks (Bangsow 2021).

The AGVs spawn in the garage below the transport routes when the simulation starts. By the concept, the number of spawned AGVs is set to two by the variable numAGV. The source of the products is linked to a buffer output that delivers the products to the AGVs. In the simulated scenario, there are two products ("Part1" and "Part2") that are homogeneous in their characteristics but differ in their destination. According to the Work Plan table, which defines the routes of the products, one part must be conveyed to the first station on the right side of the model and the other to the second station on the left side of the model. In addition to the production sequence, the work schedule also includes the definition of the setup and processing times of the stations. Adding more stations makes this model flexible and can be extended as long as the work schedule is updated simultaneously. The number of products generated by the output source in each interval can be varied. In the case study, the interval is defined as one day. This allows the daily production quantity to be specified. This was realized in the simulation by a generator that changes the time interval at which the source produces the products according to the ProductInterval table. In the simulation, the two endpoints of the transport routes are indicated by two station objects. Each station is preceded by a buffer object that receives the incoming products. The simulation uses the buffer to temporarily store parts if components cannot be processed in the station in time. A buffer is not decisive for the simulated case since capacities, setup, and processing times are calculated accordingly so that the products can be shipped at the right time. However, since the simulation is intended to be arbitrarily extendable in the future, the buffer was kept as a connecting component. The buffer type is configured to be a queue. As a result, the products leave the buffer in the same order as they entered (first-in-first-out principle). All objects must be assigned the correct parameters for the proper production sequence to be created and later automated. The essential simulation entity is the AGV unit itself. More specifically, it is provided with user-defined methods that define the underlying logic of its operation. One of the essential methods is doJob, which specifies that an empty AGV should move to the source to pick up a new part and proceed to the new job's destination. The method also describes the battery charging procedure. If the AGV's state of charge sinks below the defined battery reserve threshold, the vehicle checks the availability of the charging stations and travels to the next unoccupied station. Upon arrival, the AGV recharges up to the defined capacity (e.g., 90 % of the maximum capacity).

Using Plant Simulation, the properties of objects and the processing logic can be automated by so-called methods written in the SimTalk programming language. In the presented simulation, eight methods ensure the correct operation of the targeted process. Some methods rely on the data provided by tables. The method init creates the AGVs and resets the data of possible previous simulation runs. It also starts the method MediatorControl, which reads the JobTable, selects the AGV based on the chosen strategy, and sends the selected AGV to the determined destination. The two selectable strategies are “Everytime the First” and “the nearest”, which define if the next AGV is selected based on the execution sequence or the distance to the model’s source. The JobTable contains the starting point of a transport (job), which is the location of the product (in the simulated use case, always the buffer-out of the source) and the destination of the product, which depends on the product one of the two buffer-in objects of the stations. This table is written by the doTransport method, which defines the following due jobs based on the spawned products. The targeted station is determined by the method getNextStation, which transfers the information of the Workplan into actual jobs. It creates a list of stations based on the data in the Workplan. After that, another list is created, which contains only free stations. A station is perceived as free if it is not yet assigned or reserved for an active job. The EndSim method adds the route length of the jobs to the variable TotalDistance, which is displayed on the simulation’s root level. The last method, which affects the simulation, is Reset. Its task is to reset the diagram data. The additional method, writeData, is also created to write all relevant AGV and charging station data into several tables for later analysis.

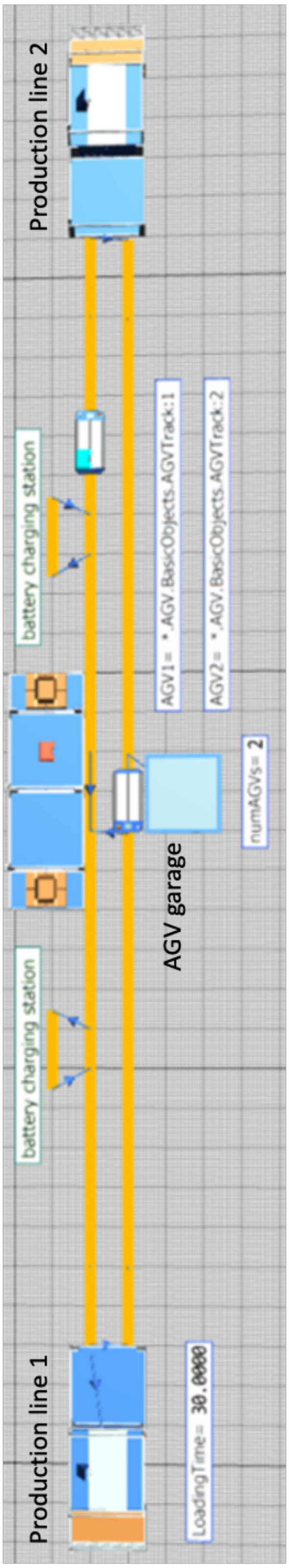



Figure 6.2: Chemicals production simulation model with AGV operation

#### 6.1.1.4 Simulation Model Results

The results of the developed simulation experiment are shown and interpreted in this chapter. The simulation time is set to one year to collect data per minute to validate AGV batteries' approach to minimalize peak loads in a manufacturing company. The simulation generated data for two AGVs and two charging stations. This simulation experiment created 525,600 data sets per AGV and charging station. The simulated charging station data is illustrated in Figure C.. They are:

- currentTime: Current time
- csID: Charging station ID
- csAvailability: Charging station availability

The simulated AGV data is shown in Figure C.. They are:

- currentTime: Current time
- agvID: AGV ID
- agvAvailability: AGV availability
- socAGV: SOC of the AGV battery
- agvLatPosition: AGV position on the X axis
- agvLngPosition: AGV position on the Y-axis
- velocityAGV: AGV velocity

After gathering the simulation data, the following AGV results were determined and presented in Table 6.2. It is noted that both AGVs operate only about 9 % of their time. The simulation results indicate that they idle over 81 % of their time per year. Due to the idle time, the AGVs can be applied as energy storage in this company and used as transport vehicles to reduce peak loads in production.

Table 6.2: AGV simulation results of the CMUC in one year

| AGV Status | AGV1 | AGV2 |
|---|---|---|
| **working** | 8.9 % | 8.5 % |
| **idle** | 81.2 % | 81.7 % |
| **charging** | 9.9 % | 9.9 % |

Table 6.3 shows the simulation results of the charging stations for one year. The second charging station was almost not used by AGVs. Therefore, reducing the number of charging stations to one for this use case would be possible. However, it needs to be investigated whether it is economical to have a second charging station when AGVs discharge their batteries during peak hours to help the company grid reduce peak production loads. Two charging stations are required for tandem operation.

Table 6.3: Charging station simulation results of the CMUC in one year

| CS Status | CS 1 | CS 2 |
|---|---|---|
| **working** | 20.5 % | 0.2 % |
| **idle** | 79.5 % | 99.8 % |

### 6.1.2 Plastic Manufacturing Scenario

#### 6.1.2.1 Company Introduction

The second use case scenario company is a metal, plastic, and electronic manufacturer for various industries, especially the automotive industry. The factory of company consists of a warehouse and a production line. The warehouse of company is 60 meters away from the production line. The products are transported by the logistic workers approximately twenty times per hour. Two employees work one shift (eight hours) daily in the company. With the help of this information, the concept's assumptions are described in the next chapter.

The energy consumption data from the company of the first use case is anonymized, shown in Figure 6.3.

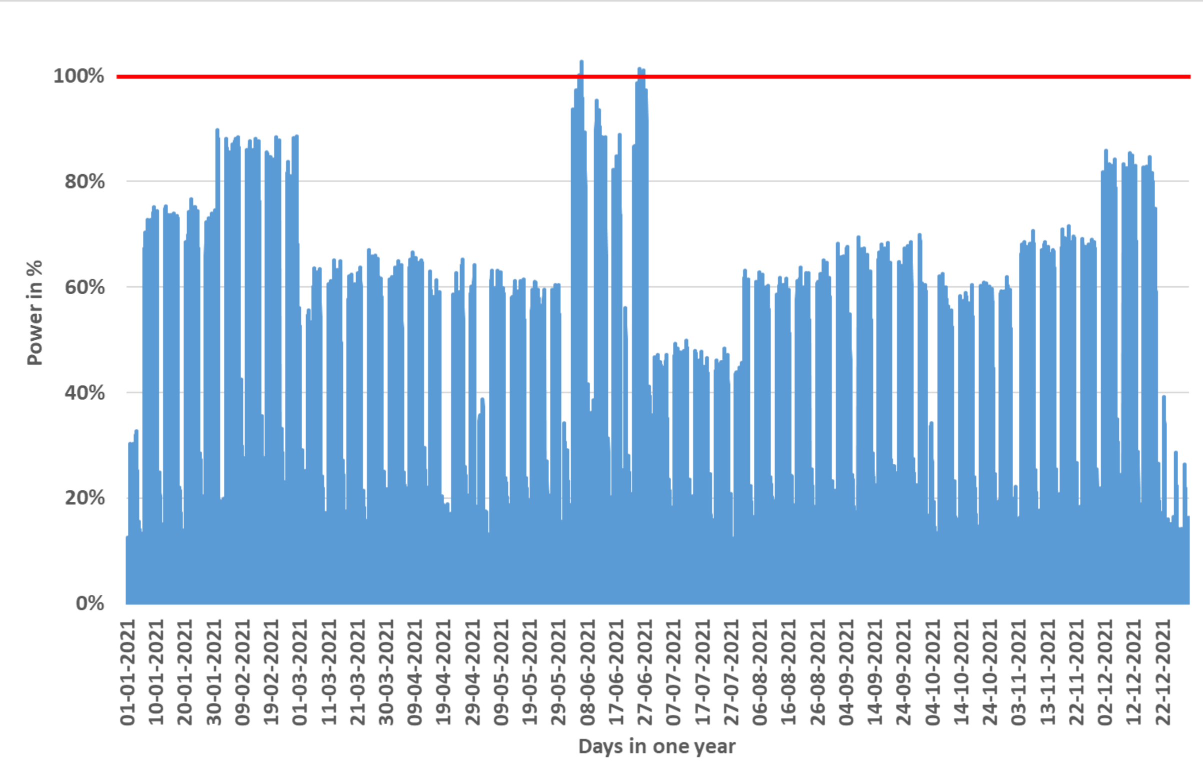



Figure 6.3: Plastics manufacturing company - energy consumption data

#### 6.1.2.2 Simulation Concept

The simulation model should be developed with the AGV operation. The following assumptions in the simulation model are made for the logistics processes of the company to realize a realistic simulation:

- The simulation duration is set to 1-year simulation time from 01.01.2021 to 31.12.2021. To calculate how many peak loads can be covered with AGV batteries, AGV data for one year should be generated.
- The transport processes of one product are considered.

- The interval of the production orders (max. in 3 minutes and min. in 37 minutes) is calculated for one year per day using the energy consumption data set in the simulation.
- An AGV has an average speed of 1 m/s (approx. 4 km/h).
- The SOC limits of the AGV are predefined (20-90 % for the lithium battery saving). AGV shall drive to the charging station if the lower SOC limit is exceeded.
- All AGVs have an initial value of 50 % for the battery SOC.
- One AGV garage is located in the factory layout and consists of two AGVs. No employees are used for intralogistics. Instead, the AGVs have performed the intralogistics tasks.
- AGVs transport the product from the warehouse to the production line.
- AGVs should work between 9 and 17 am per day.
- Two charging stations are simulated so that AGV batteries are charged.

The same data from KUKA KMP 1500 AGV (KUKA AG 2016) is used as the AGV data for this simulation model. After the assumptions are determined, the simulation model is developed. The next chapter presents the model description.

#### 6.1.2.3 Simulation Model Description

The simulation model of the first use case scenario was adjusted. All methods from the first simulation model were applied in this model. The only difference is that the AGV route appears different. The AGVs should drive from the warehouse directly to the production line. There are two charging stations between these two. Instead of two products, only one product is considered in this model. The simulation model is indicated in Figure 6.4.

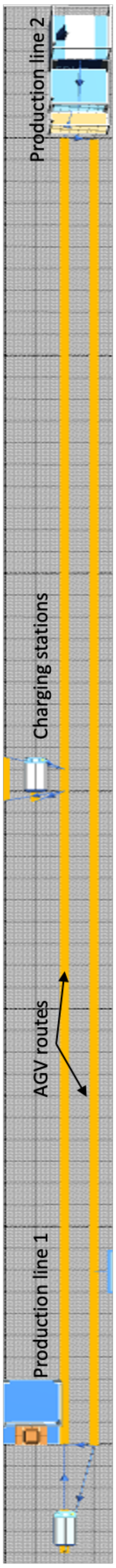



Figure 6.4: Plastics production simulation model with AGV operation

#### 6.1.2.4 Simulation Model Results

The results of the developed simulation experiment are shown and interpreted in this chapter. The simulation time is set to one year to collect data per minute to validate AGV batteries' approach to minimalize peak loads in a manufacturing company. The simulation generated data for two AGVs and two charging stations. In addition, 525,600 data sets were created per AGV and charging station in this simulation model.

After the simulation data was collected, the following AGV results were obtained and shown in Table 6.4. It is noted that both AGVs work approximately only 11 % of their time. The simulation results show that they have over 83 % idle time per year. The idle time allows the AGVs to be used as transport vehicles and energy storage in this company to reduce peak loads in production. In future work, sensitivity analysis will be conducted to check different implementation strategies, whether the AGVs should be reduced to save investment costs or the AGVs should be implemented as in the simulation to reduce the peak load fees.

Table 6.4: AGV simulation results of the PMUC in one year

| AGV Status | AGV3 | AGV4 |
|---|---|---|
| **working** | 11.2 % | 11.3 % |
| **idle** | 83 % | 82.9 % |
| **charging** | 5.8 % | 5.8 % |

Table 6.5 indicates the simulation results of the charging stations in one year. It is observed that charging station 4 was not used by AGVs like charging station 3. Therefore, reducing the number of charging stations for this use case would be conceivable. However, it has to be investigated whether it is economical to have a second charging station if the AGVs discharge their batteries in peak times to support the company grid to reduce peak loads in production. Two charging stations are required to operate in tandem.

Table 6.5: Charging station simulation results of the PMUC in one year

| CS Status | CS 3 | CS 4 |
|---|---|---|
| **working** | 24.1 % | 6.7 % |
| **idle** | 75.9 % | 93.3 % |

### 6.1.3 Battery Manufacturing Scenario

#### 6.1.3.1 Company Introduction

The company from the third use case scenario for which the simulation was developed is a battery manufacturer that produces micro batteries, household batteries, ESS to customized battery solutions for a wide range of applications. The factory of company consists of different production lines. Only AGVs transporting products and items between two production lines are considered and work three daily shifts.

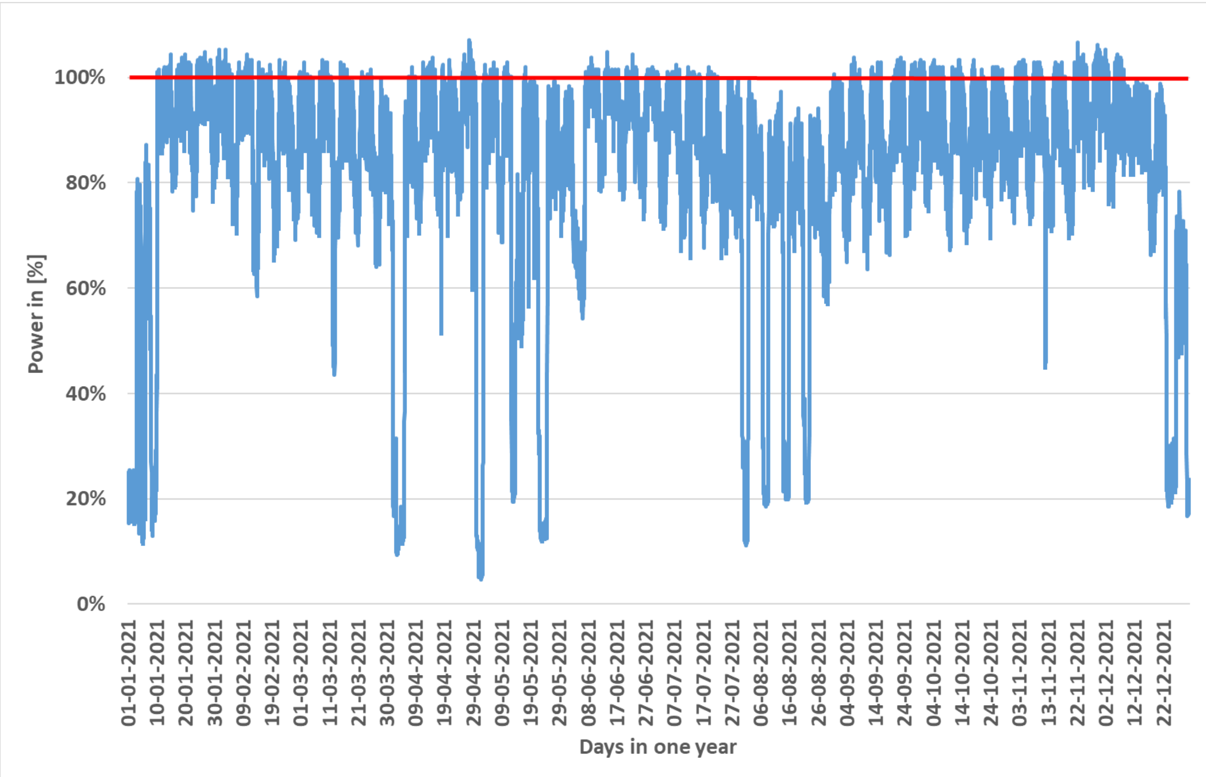



Figure 6.5: Battery manufacturing company - energy consumption data

The energy consumption data from the company of the third use case is anonymized, shown in Figure 6.5.

With the help of all information described above, the concept's assumptions are determined in the next chapter.

#### 6.1.3.2 Simulation Concept

The company has different AGVs; only 2 AGVs of this company are considered in the simulation concept. The problem was that the company needed to record the data like SOC from the AGV batteries. Therefore, a realistic simulation for these AGVs should be developed to generate all required data for the BUOS. The following assumptions in the simulation model are made for the logistics processes of the company to realize a realistic simulation:

- The simulation duration is set to 1-year simulation time from 01.01.2021 to 31.12.2021. To calculate how many peak loads can be covered with AGV batteries, AGV data for one year should be generated.
- The transport processes of one product are considered.
- The interval of the production orders (approx. 15 minutes) is calculated for one year per day using the energy consumption data set in the simulation.
- An AGV has an average speed of 1.5 m/s (approx. 5.4 km/h).
- The SOC limits of the AGV are predefined according to the company’s battery-saving strategy (40-100 % for the lithium battery). AGV shall drive to the charging station if the lower SOC limit is exceeded.
- All AGVs have an initial value of 50 % for the battery SOC.
- One AGV garage is located in the factory layout and consists of two AGVs.
- AGVs transport the product between two production lines.
- AGVs should work three shifts per day.

Two charging stations are simulated so that AGV batteries are charged. The AGV data from the battery manufacturing company is used as the AGV data to generate a realistic simulation model. It is shown in Table 6.6.

Table 6.6: AGV data of the battery manufacturing company

| Feature | Value |
|---|---|
| **AGV battery charging current** | 48 A |
| **AGV battery charging voltage** | 75 V |
| **AGV battery capacity energy** | 3,600 Wh |
| **AGV battery charging time** | 1 hour (up to 100 %) |
| **AGV driving consumption** | ca. 18 A |

### 6.1.3.3 Simulation Model Description

The simulation model of the first use case scenario was adjusted. All methods from the first simulation model were applied in this model. The only difference is that the AGV route appears different. The AGVs should drive between two production lines. There are two charging stations between these two. Instead of two products, only one product is considered in this model. The simulation model is indicated in Figure 6.6.

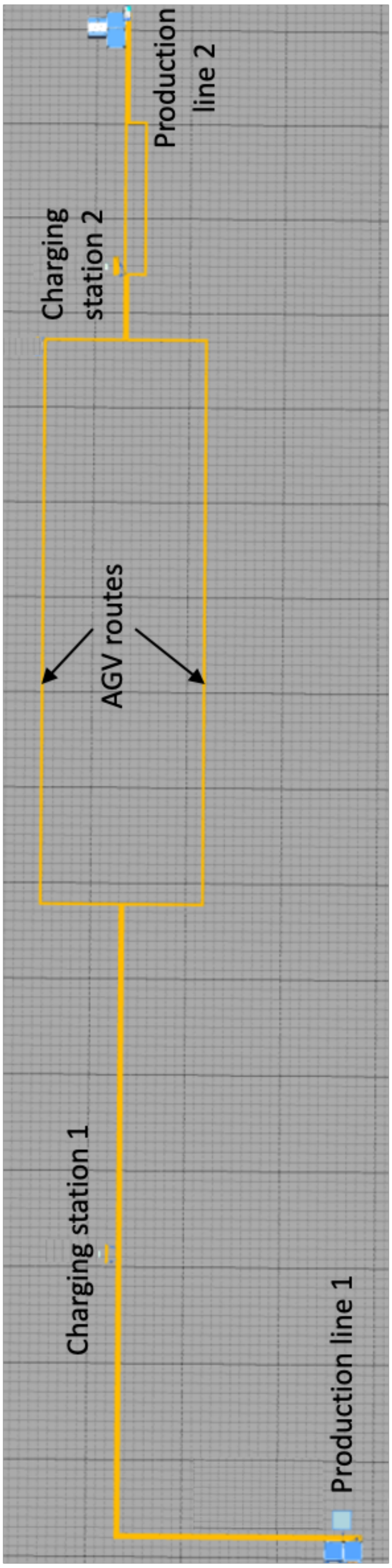



Figure 6.6: Battery production simulation model with AGV operation

#### 6.1.3.4 Simulation Model Results

The results of the developed simulation experiment are shown and interpreted in this chapter. The simulation time is set to one year to collect data per minute to validate AGV batteries' approach to minimalize peak loads in a manufacturing company. The simulation generated data for two AGVs and two charging stations. In addition, 525,600 data were created per AGV and charging station in this simulation model.

After the simulation data was collected, the following AGV results were obtained and shown in Table 6.7. It is noted that both AGVs work approximately only 39 % of their time. The simulation results show that they have over 53 % idle time per year. The idle time allows the AGVs to be used as transport vehicles and energy storage in this company to reduce peak loads in production. In future work, sensitivity analysis will be conducted to check different implementation strategies, whether the AGVs should be reduced to save investment costs or the AGVs should be implemented as in the simulation to reduce the peak load fees.

Table 6.7: AGV simulation results of the BMUC in one year

| AGV Status | AGV5 | AGV6 |
|---|---|---|
| **working** | 38.3 % | 38.3 % |
| **idle** | 53.4 % | 53.3 % |
| **charging** | 8.3 % | 8.4 % |

Table 6.8 indicates the simulation results of the charging stations in one year. It is observed that charging station 5 works only 7 % of the time while charging station 6 works approximately 10 % of the time. Both charging stations have enough idle time so that the AGVs can use them to discharge their batteries to cover the peak loads of the battery manufacturing company.

Table 6.8: Charging station simulation results of the BMUC in one year

| CS Status | CS 5 | CS 6 |
|---|---|---|
| **working** | 6.7 % | 10.1 % |
| **idle** | 93.3 % | 89.9 % |

## 6.2 Performing Sensitivity Analysis

To perform the sensitivity analysis, the procedure described in chapter 4.4.3 is considered.

First, the question is formulated that the analysis seeks to answer to define the objective. The formulated question is how cost-effective it is for an example company to use AGVs with the BUOS as an ESS and a transportation system. Then, a suitable output is defined. It is cost savings in peak load reduction for manufacturing companies with AGV batteries. In the next step, the input factors should be defined. The defined input factors for the use cases are variables (AGV battery capacity, AGV amount, charging station amount, electricity cost, and peak electricity cost of the sample company) affecting the output.

The selected input examples of different use cases, such as CMUC, PMUC, and BMUC, are presented in the next chapter. The experiments in four different categories are planned to conduct. The main experiment consists of the following input variables (see Table 6.9).

Table 6.9: Main experiment input values

| Input variables | CMUC | PMUC | BMUC |
|---|---|---|---|
| **AGV battery capacity in kWh** | 9.984 | 9.984 | 3.6 |
| **AGV amount** | 2 | 2 | 2 |
| **Charging station amount** | 2 | 2 | 2 |
| **Electricity costs in cents/kW** | 14 | 16 | 13 |
| **Peak power price in €/kW** | 114.78 | 90 | 110 |

The other experiments are iterated from the main experiment. In the first category, the AGV battery capacity is increased to see the impact of the energy on cost savings. Then, the electricity costs are changed to identify the effect of the reduced and increased electricity costs on cost savings. The peak electricity cost is adjusted to investigate the relation between the peak electricity cost and cost savings in the third category. In the last category, the AGV amount and the charging station amount are increased to validate the impact of the increasing AGVs and charging stations on cost savings. The results of the output evaluation can be found in the next chapter.

## 6.3 Parameter Variation and Validation Results

In the sensitivity analysis, the experiments performed with different input parameters for each use case are clustered in four different categories. This selection assessed the effect of the changed input variables on the output variable (cost savings). In this way, it was determined whether the BUOS software is cost-efficient, when and with which changed input variables it becomes even more cost-efficient for the companies.

In the first category, the influence of the parameters such as AGV battery capacity and charging station power on the cost savings was inspected. Then, it was investigated what kind of an effect the electricity costs have on cost savings. The third category shows the cost savings results for different peak electricity costs. The last category theoretically investigates how the cost savings change if the AGV and charging station amounts in the companies of three use cases are increased.

### 6.3.1 AGV Battery Capacity Adjustment

Three experiments per use case were conducted in this chapter. The battery capacity of AGVs was increased to calculate the cost savings for three different use cases, such as CMUC, PMUC, and BMUC, and to determine the relationship between AGV battery capacity and cost savings. During the experiment execution, it was found that the cost savings only increase with increased AGV battery capacity if the charging station power is also raised. Otherwise, cost savings remain the same. Therefore, the following parameters from Table 6.10 are used to calculate cost savings.

Table 6.10: Experiments' parameter set with AGV battery capacity adjustment

| # | Use case name | AGV battery capacity in kWh | AGV amount | Charging station amount | Electricity costs in cents/kWh | Peak electricity costs in €/kW | Charging station power in kW |
|---|---|---|---|---|---|---|---|
| **1** | CMUC | 9.984 | 2 | 2 | 14 | 114.78 | 4.992 |
| **2** | CMUC | 19.968 | 2 | 2 | 14 | 114.78 | 9.984 |
| **3** | CMUC | 39.936 | 2 | 2 | 14 | 114.78 | 19.968 |
| **4** | PMUC | 9.984 | 2 | 2 | 16 | 90 | 4.992 |
| **5** | PMUC | 19.968 | 2 | 2 | 16 | 90 | 9.984 |
| **6** | PMUC | 39.936 | 2 | 2 | 16 | 90 | 19.968 |
| **7** | BMUC | 3.6 | 2 | 2 | 13 | 110 | 3.6 |
| **8** | BMUC | 7.2 | 2 | 2 | 13 | 110 | 7.2 |
| **9** | BMUC | 14.4 | 2 | 2 | 13 | 110 | 14.4 |

Figure 6.7 illustrates that the cost savings are raised with increased AGV battery capacity in CMUC. But the relationship between the two parameters is not linear. It is not economical for the company to purchase AGVs with higher energy to reduce peak loads in its manufacturing plant. If the battery cost per kWh is assumed to be 127.27 € (Forbes 2020), an AGV with doubled energy (ca. 20 kWh) will cost 1,270.66 € more. This purchase's return of investment (ROI) would be over 200 years in CMUC, which is unrealistic. In addition, it is stated here that the power of the charging stations should be increased to achieve the following cost savings in the diagram. With this additional cost, buying AGVs with higher energy is not recommended if the company does not need them.

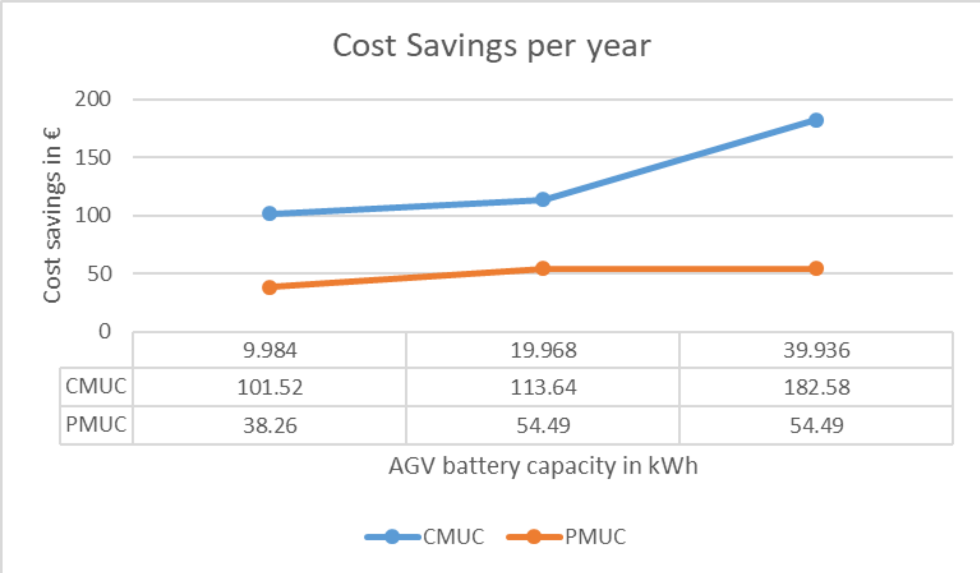



Figure 6.7: CMUC and BMUC cost savings with the adjusted AGV battery capacity

It can be interpreted from the results that the battery manufacturing company can make a minimum profit of 132.56 € per year when available AGVs are used as both energy storage and transport vehicles (see Figure 6.8). Compared to other use cases, it is observed in BMUC that the cost savings have almost a linear relationship to AGV battery capacity.

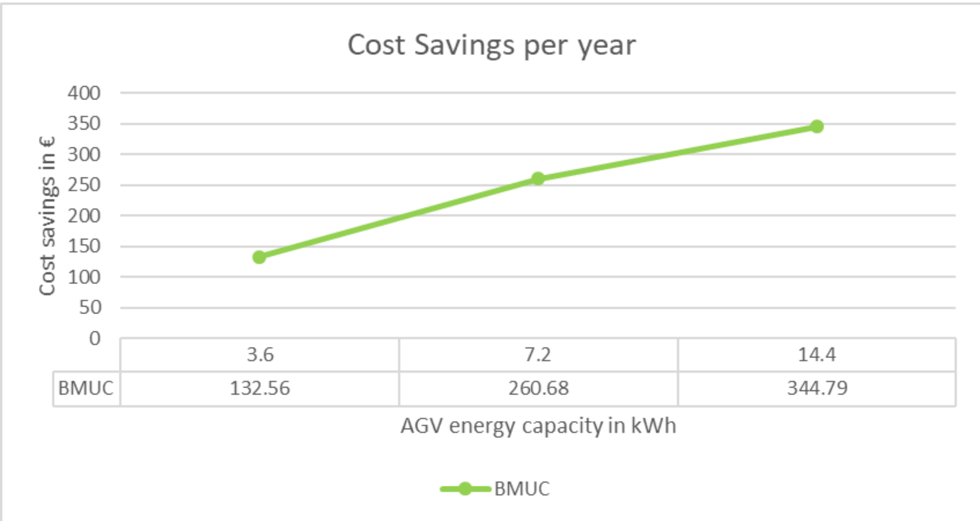



Figure 6.8: BMUC cost savings with the adjusted AGV battery capacity

In PMUC, it is observed that the cost savings first increase if the AGV battery capacity and power of charging stations are doubled. Still, in a quadrupling of AGV battery capacity, the company's cost savings remain the same. The reduced peak amounts can explain this result in PMUC. That signifies that AGVs with quadrupled energy have reduced some peaks, but this power was not enough to reduce the peaks, so the company could not reduce the costs caused by the peak power.

Figure 6.9 shows the reduced peak load of both companies and supports the previous results presented with AGV battery capacity and peak amounts. 67.8 % of the company's peak load in CMUC was covered by AGV batteries, which have approximately 40 kWh of energy, while this percentage was only 30.6 % in PMUC.

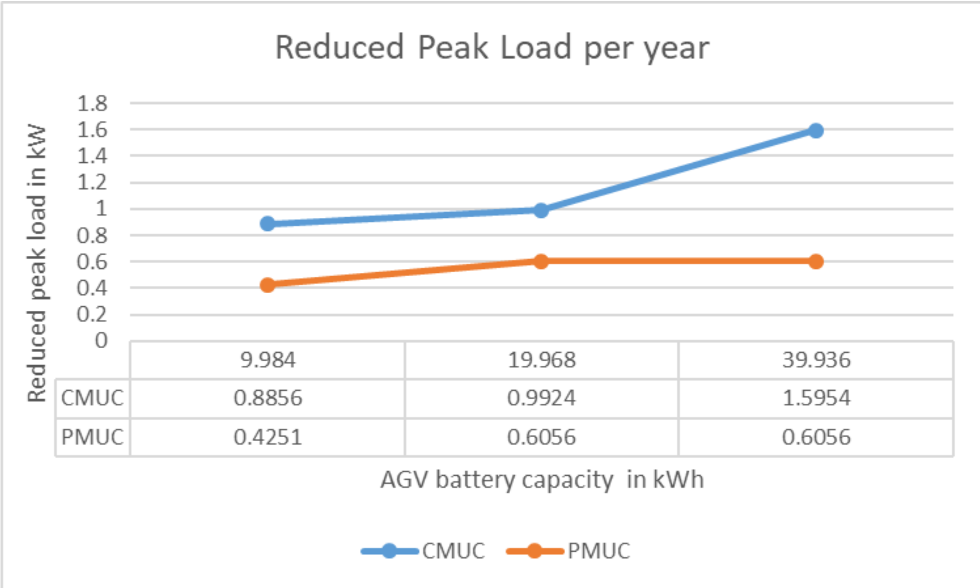



Figure 6.9: CMUC and PMUC reduced peak load with adjusted AGV battery capacity

AGV battery capacity is linearly related to cost savings in the BMUC (see Figure 6.10). Furthermore, more than 2 AGVs are needed to cover the total peak power of the company.

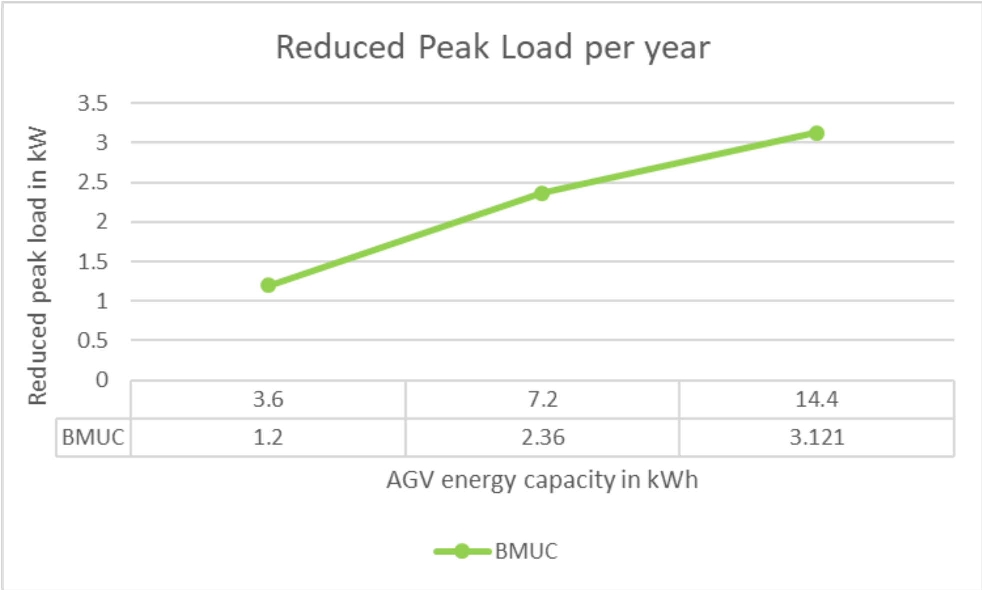



Figure 6.10: BMUC reduced peak load with adjusted AGV battery capacity

The sensitivity analysis results in this chapter represent that the AGV battery capacity has a weak impact on cost savings in CMUC and PMUC. But according to the ROI calculation of the AGVs with higher battery capacity, it is stated that both companies should refrain from making investments in the AGVs with higher battery capacity to reduce their current peak load so that they can save money. Unlike these use cases, AGV battery capacity has a linear relationship with cost savings in BMUC.

### 6.3.2 Electricity Cost Parameter Adjustment

This chapter investigates how a manufacturing company's increasing and decreasing electrical costs can affect cost savings by using peak shaving. Table 6.11 illustrates four experiments per use case that were performed. The electricity costs are iterated in these experiments; other parameters remain the same.

Table 6.11: Experiments' parameter set with electricity costs adjustment

| # | Use case name | AGV battery capacity in kWh | AGV amount | Charging station amount | Electricity costs in cents/kWh | Peak electricity costs in €/kW | Charging station power in kW |
|---|---|---|---|---|---|---|---|
| **1** | CMUC | 9.984 | 2 | 2 | 28 | 114.78 | 4.992 |
| **2** | CMUC | 9.984 | 2 | 2 | 14 | 114.78 | 4.992 |
| **3** | CMUC | 9.984 | 2 | 2 | 7 | 114.78 | 4.992 |
| **4** | CMUC | 9.984 | 2 | 2 | 3.5 | 114.78 | 4.992 |
| **5** | PMUC | 9.984 | 2 | 2 | 32 | 90 | 4.992 |
| **6** | PMUC | 9.984 | 2 | 2 | 16 | 90 | 4.992 |
| **7** | PMUC | 9.984 | 2 | 2 | 8 | 90 | 4.992 |
| **8** | PMUC | 9.984 | 2 | 2 | 4 | 90 | 4.992 |
| **9** | BMUC | 3.6 | 2 | 2 | 6.5 | 110 | 3.6 |
| **10** | BMUC | 3.6 | 2 | 2 | 13 | 110 | 3.6 |
| **11** | BMUC | 3.6 | 2 | 2 | 26 | 110 | 3.6 |
| **12** | BMUC | 3.6 | 2 | 2 | 52 | 110 | 3.6 |

The cost savings with adjusted electricity costs in CMUC are illustrated in Figure 6.11. The electricity costs are between 3.5 and 28 cents in this use case. The results show that electricity costs negatively impact cost savings, which can even be ignored. The AGV batteries should be discharged to cover the peak power of the company. For example, 114.78 € in CMUC and 90 € in PMUC are saved per kW. These AGV batteries should be charged later so AGV can complete its tasks in production. The electricity cost is a few cents per kW. This is a meager amount when the electricity cost is compared to the peak electricity cost. Therefore, this weak effect of the electricity costs on cost savings can be explained.

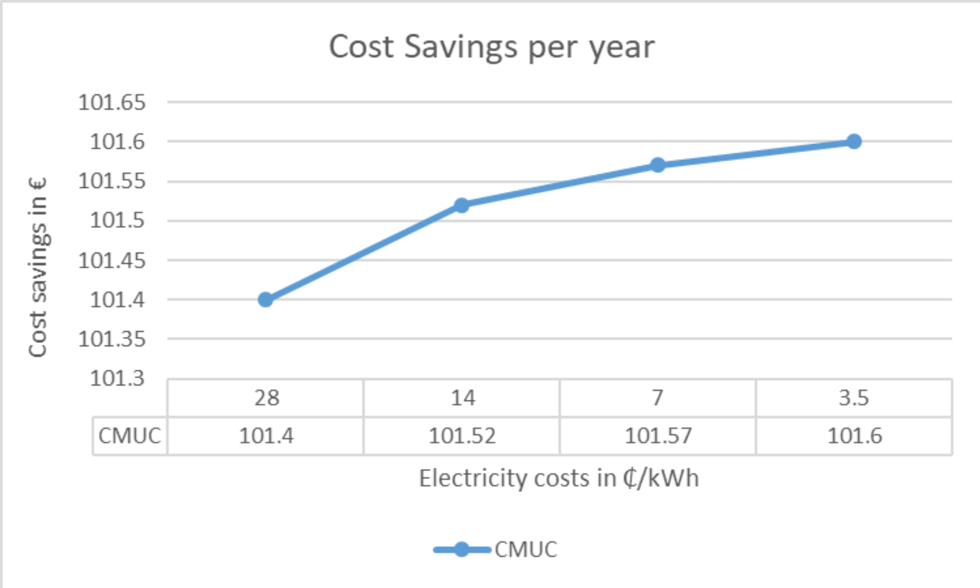



Figure 6.11: CMUC cost savings with adjusted electricity costs

The same result pattern can be seen in Figure 6.12. This weak impact of electricity costs has changed only the decimal places of the cost savings, not shown in the figure. Therefore, the cost savings have remained the same.

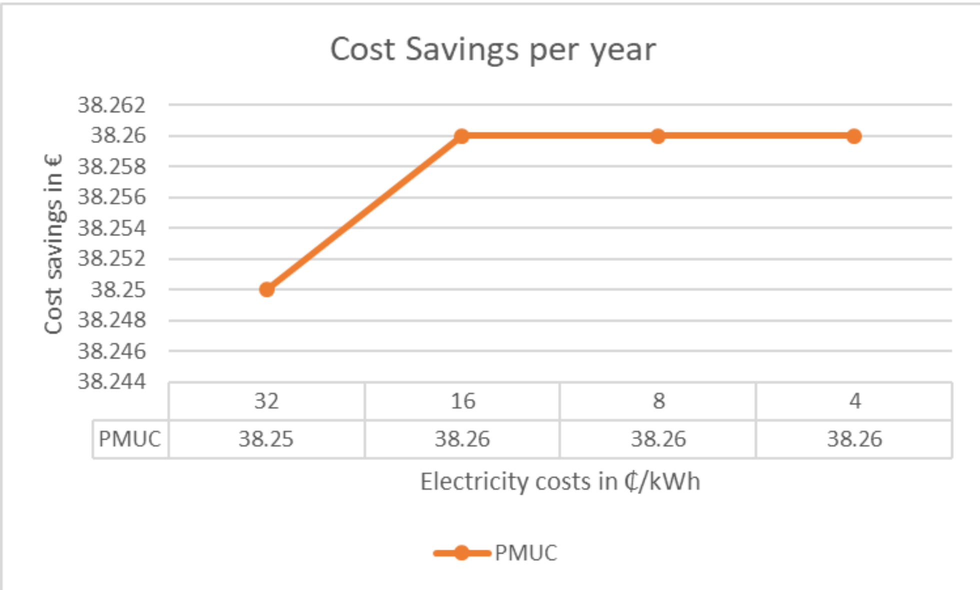



Figure 6.12: PMUC cost savings with adjusted electricity costs

Figure 6.13 shows the cost savings with adjusted electricity costs in BMUC. Electricity costs have a minor impact on cost savings and can even be neglected. The AGV batteries should be discharged to cover the peak power of the company. For example, 110 € in the battery manufacturing company is saved per kW. These AGV batteries should be recharged later so the AGV can perform its tasks in production. The electricity cost is a few cents per kWh. This is a meager amount when compared to peak electricity costs.

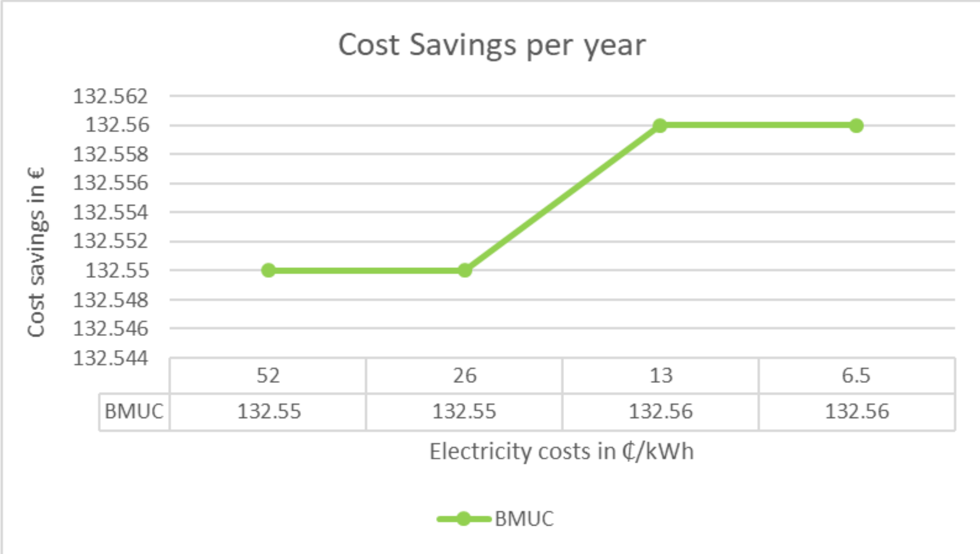



Figure 6.13: BMUC cost savings with adjusted electricity costs

From the experiment results, it can be interpreted that electricity costs have a weak effect on cost savings. The higher the electricity costs are for the companies, the more the cost savings are reduced. The increased electricity cost can bring a disadvantage for the companies in the future, but they have almost no impact on the peak shaving use cases.

### 6.3.3 Peak Electricity Cost Parameter Adjustment

According to the international climate conference in Paris in 2015 (BMWi 2018, p. 8), the EU has agreed to increase the share of renewable energies by at least 32 % in 2030. The electricity generated from renewable energy technologies varies remarkably, which may cause more instability in the future in the entire power grid. This problem can lead to an increase in peak electricity costs for the companies. Therefore, four experiments per use case (see Table 6.12) are performed to find the relationship between peak electricity costs and cost savings.

Table 6.12: Experiments' parameter set with peak electricity cost adjustment

| # | Use case name | AGV battery capacity in kWh | AGV amount | Charging station amount | Electricity costs in cents/kWh | Peak electricity costs in €/kW | Charging station power in kW |
|---|---|---|---|---|---|---|---|
| **1** | CMUC | 9.984 | 2 | 2 | 14 | 114.78 | 4.992 |
| **2** | CMUC | 9.984 | 2 | 2 | 14 | 229.56 | 4.992 |
| **3** | CMUC | 9.984 | 2 | 2 | 14 | 459.12 | 4.992 |
| **4** | CMUC | 9.984 | 2 | 2 | 14 | 918.24 | 4.992 |
| **5** | PMUC | 9.984 | 2 | 2 | 16 | 90 | 4.992 |
| **6** | PMUC | 9.984 | 2 | 2 | 16 | 180 | 4.992 |
| **7** | PMUC | 9.984 | 2 | 2 | 16 | 360 | 4.992 |
| **8** | PMUC | 9.984 | 2 | 2 | 16 | 720 | 4.992 |
| **9** | BMUC | 3.6 | 2 | 2 | 13 | 110 | 3.6 |
| **10** | BMUC | 3.6 | 2 | 2 | 13 | 220 | 3.6 |
| **11** | BMUC | 3.6 | 2 | 2 | 13 | 440 | 3.6 |
| **12** | BMUC | 3.6 | 2 | 2 | 13 | 880 | 3.6 |

It is observed in Figure 6.14, Figure 6.15, and Figure 6.16 that the peak electricity costs have a linear relationship with the cost savings in all use cases (CMUC, PMUC, and BMUC). The results from three use cases show that implementing the AGV as energy storage with the BUOS service would be interesting for the companies when the peak electricity costs increase in the future.

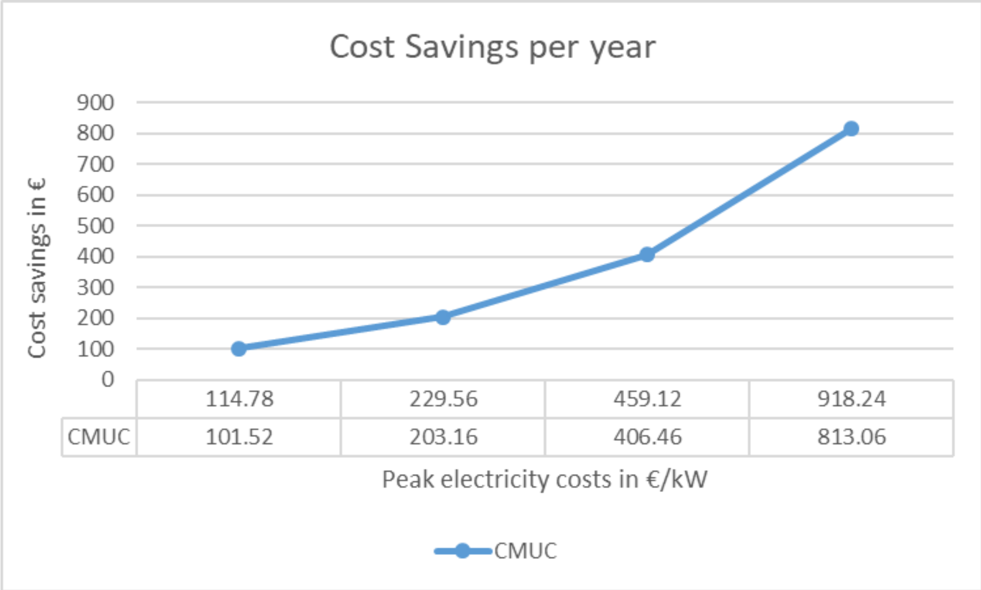



Figure 6.14: CMUC cost savings with adjusted peak electricity cost

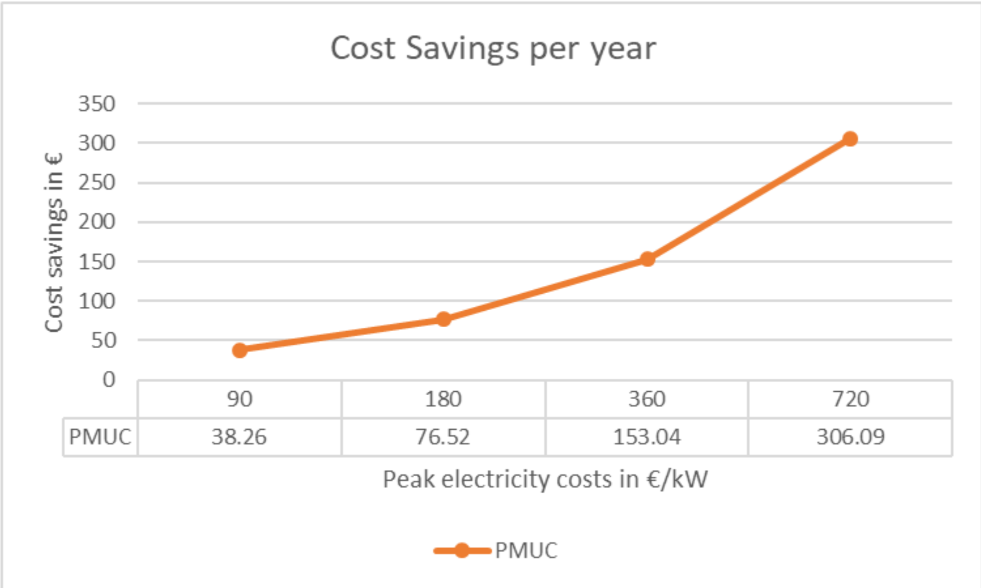



Figure 6.15: PMUC cost savings with adjusted peak electricity cost

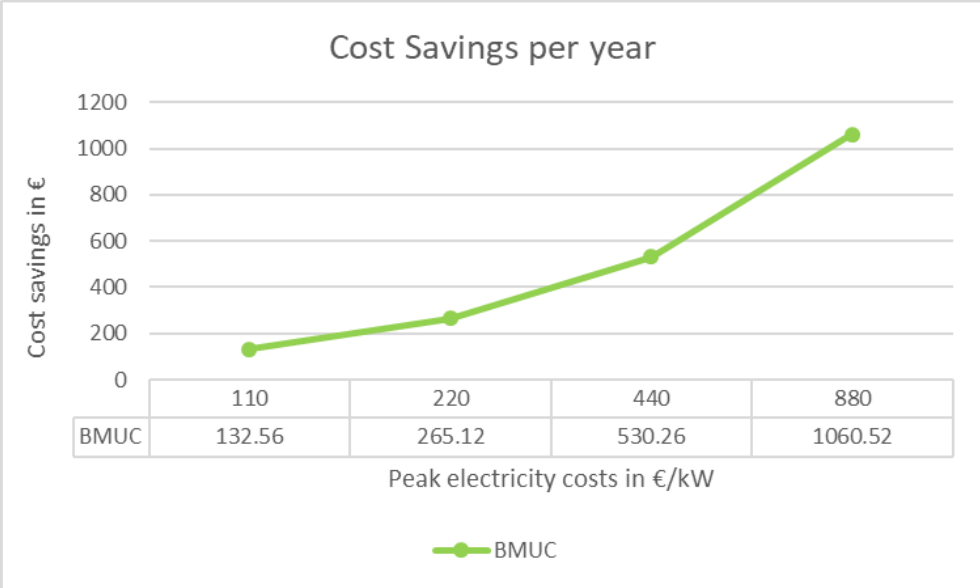



Figure 6.16: BMUC cost savings with adjusted peak electricity cost

### 6.3.4 AGV and Charging Station Amount Parameter Adjustment

The relation between cost savings and AGV charging station amounts in different use cases is theoretically investigated in this chapter.

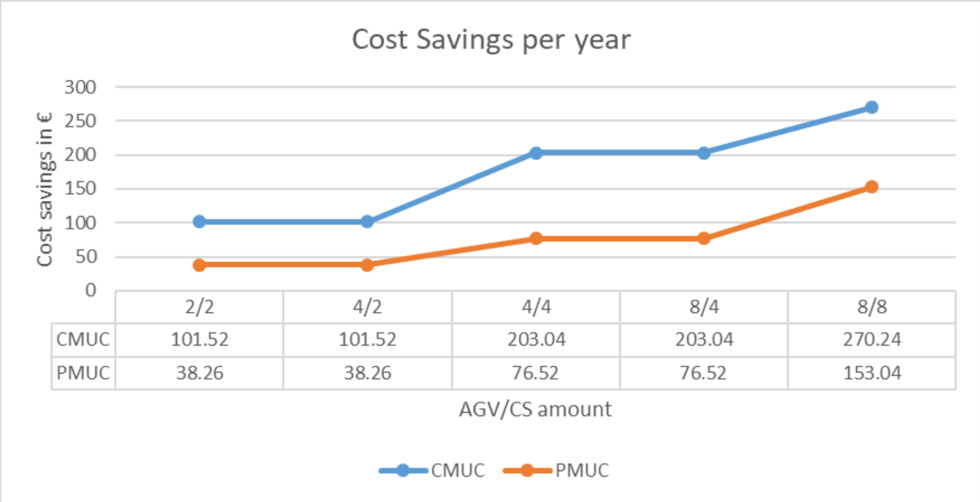
Table 6.13 shows the parameter set of ten experiments with adjusted AGV and charging station amounts. CMUC, PMUC, and BMUC have only two AGVs and two charging stations. In the following experiments, it is assumed that the new AGVs are precisely similar to the existing AGVs and have the same production tasks. It is also assumed that the charging and discharging scheduling of the new AGVs are just the same as the existing ones. Therefore, it is taken as an assumption that a new AGV requires a new charging station to discharge its battery at the same time as other AGVs to reduce peak loads for the companies in peak load times.

Table 6.13: Experiments' parameter set with AGV and CS amount adjustment

| # | Use case name | AGV battery capacity in kWh | AGV amount | Charging station amount | Electricity costs in cents/kWh | Peak electricity costs in €/kW | Charging station power in kW |
|---|---|---|---|---|---|---|---|
| **1** | CMUC | 9.984 | 2 | 2 | 14 | 114.78 | 4.992 |
| **2** | CMUC | 9.984 | 4 | 2 | 14 | 114.78 | 4.992 |
| **3** | CMUC | 9.984 | 4 | 4 | 14 | 114.78 | 4.992 |
| **4** | CMUC | 9.984 | 8 | 4 | 14 | 114.78 | 4.992 |
| **5** | CMUC | 9.984 | 8 | 8 | 14 | 114.78 | 4.992 |
| **6** | PMUC | 9.984 | 2 | 2 | 16 | 90 | 4.992 |
| **7** | PMUC | 9.984 | 4 | 2 | 16 | 90 | 4.992 |
| **8** | PMUC | 9.984 | 4 | 4 | 16 | 90 | 4.992 |
| **9** | PMUC | 9.984 | 8 | 4 | 16 | 90 | 4.992 |
| **10** | PMUC | 9.984 | 8 | 8 | 16 | 90 | 4.992 |
| **11** | BMUC | 3.6 | 2 | 2 | 13 | 110 | 3.6 |
| **12** | BMUC | 3.6 | 4 | 2 | 13 | 110 | 3.6 |
| **13** | BMUC | 3.6 | 4 | 4 | 13 | 110 | 3.6 |
| **14** | BMUC | 3.6 | 8 | 4 | 13 | 110 | 3.6 |
| **15** | BMUC | 3.6 | 8 | 8 | 13 | 110 | 3.6 |

It can be interpreted from the results (see Figure 6.17) that the company in CMUC can make a minimal profit (101.52 €) per year if existing available AGVs are used both as energy storage and as transport vehicles. It is not recommended to procure an AGV to reduce peak loads for this company. Because an AGV costs between 15,000 and 30,000 € and a new charging station costs around 2,000 € (Jan et al. 2018), the payback period ROI for this implementation would be longer than 300 years, which is not realistic and economical. This implementation may become more economical for the company as battery technology evolves and peak electricity costs increase in the coming years.

The sensitivity analysis results of the PMUC show that the company can make a minimal profit (66.82 €) per year if existing available AGVs from this use case scenario are used both as energy storage and transport vehicles. Although the profit (cost savings) was increased with four AGV operations, it is also not recommended that this company procure an AGV to reduce peak loads. Considering the AGV and charging station costs, the payback time would be more than 400 years. After the battery technology evolves and peak electricity costs increase in the coming years, this implementation can be more beneficial for this company.




| | 2/2 | 4/2 | 4/4 | 8/4 | 8/8 |
|---|---|---|---|---|---|
| CMUC | 101.52 | 101.52 | 203.04 | 203.04 | 270.24 |
| PMUC | 38.26 | 38.26 | 76.52 | 76.52 | 153.04 |

Figure 6.17: CMUC and PMUC cost savings with adjusted AGV and CS amount

Although the profit (cost savings) was increased by operating four AGVs (see Figure 6.18), it is not recommended to procure an AGV to reduce peak loads for the battery manufacturing company. If the costs of charging stations and AGVs are considered above, then the payback time ROI for this use case would also not be realistic.

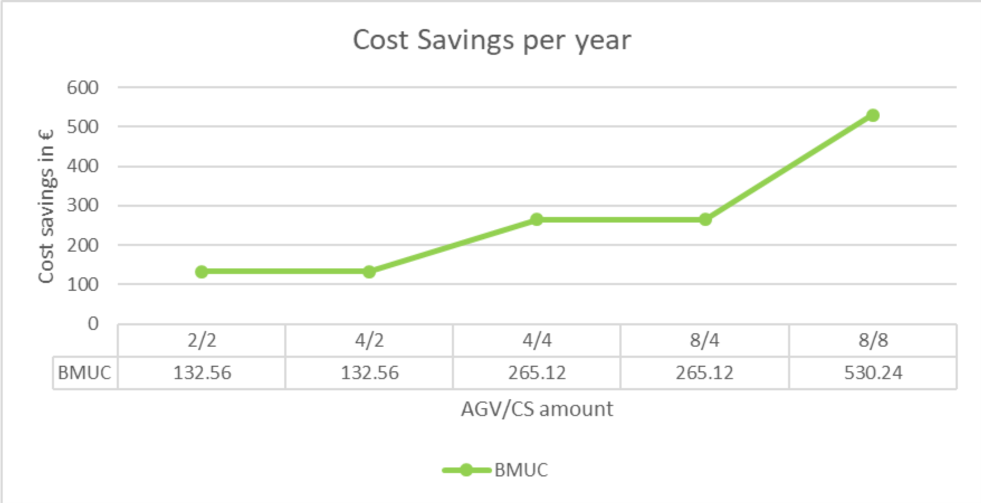



Figure 6.18: BMUC cost savings with adjusted AGV and CS amount

The results from all use cases show that implementing an AGV as energy storage with the BUOS service would be interesting for companies that utilize large AGV fleets in their logistics processes. Figure 6.19 indicates that reduced peak load in PMUC increases linearly with increased AGV and CS amount. This is not observed in CMUC (see Figure 6.20) in the last experiment because eight AGVs can cover the chemical manufacturing company's peak power for the whole year. In comparison, eight AGVs in PMUC can provide power to cover approximately 86 % peak power of the plastics manufacturing company.

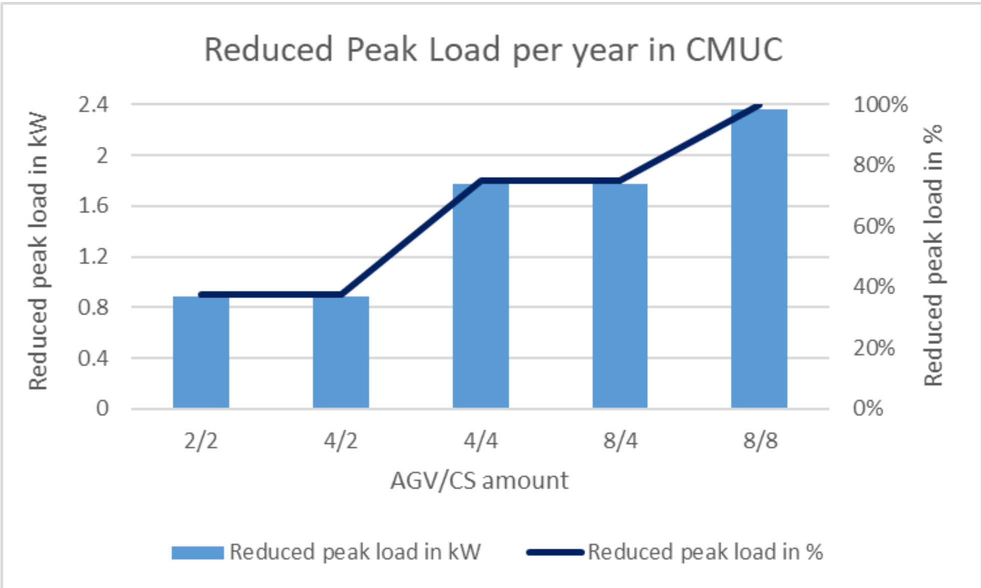



Figure 6.19: CMUC reduced peak load with adjusted AGV and CS amount

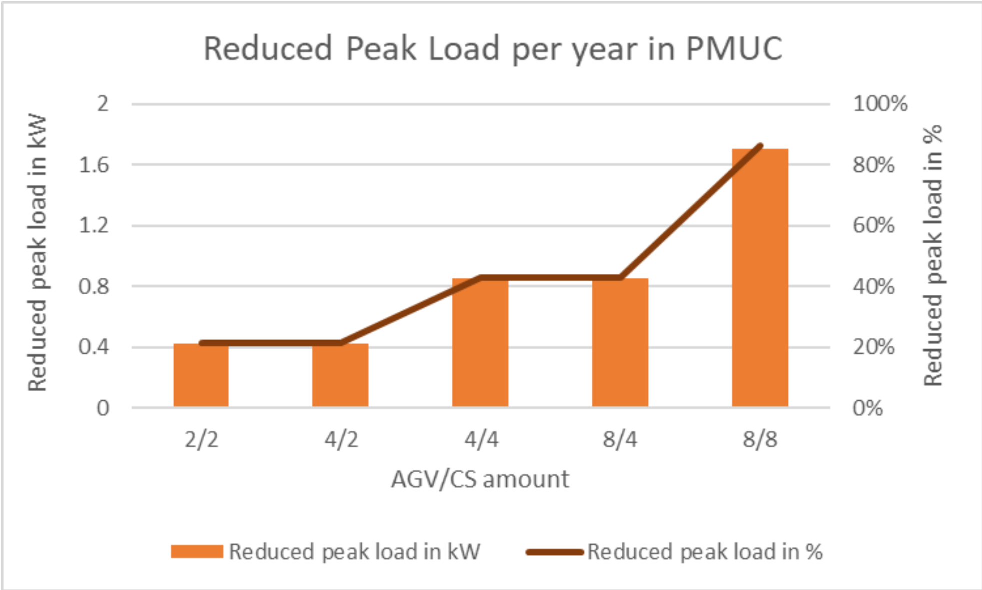



Figure 6.20: PMUC reduced peak load with adjusted AGV and CS amount

Figure 6.21 shows that the reduced peak load in BMUC increases in a linear relationship with the number of AGVs and charging stations. 8 AGVs in BMUC can cover about 16 % of the peak power of the battery manufacturing company.

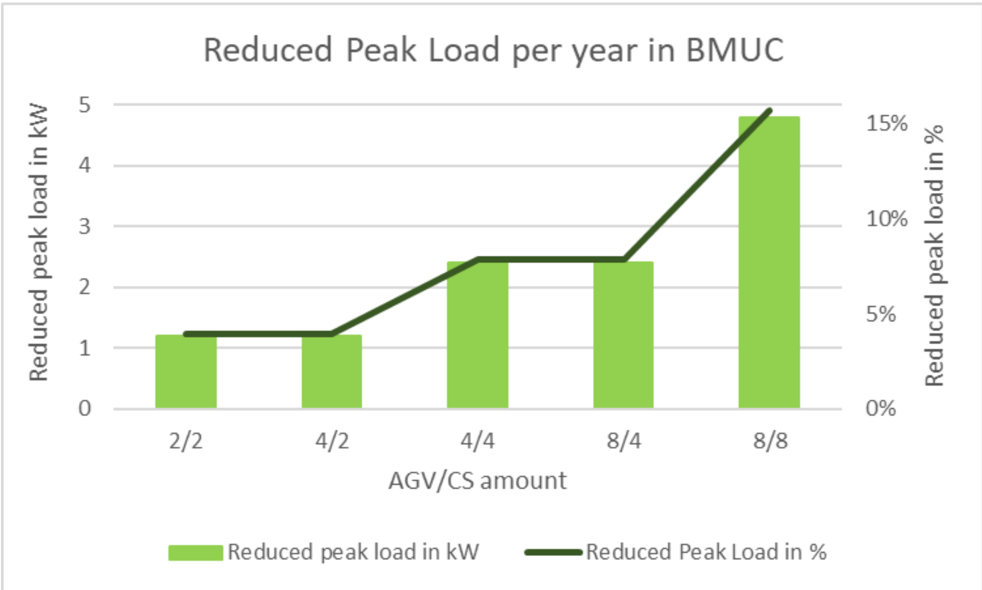



Figure 6.21: BMUC reduced peak load with adjusted AGV and CS amount

The next chapter describes the critical appraisal of this work. First, the fulfillment of the requirements of this work is evaluated, then it is verified how and in which chapters the research questions of this dissertation were answered.

# 7 Critical Appraisal

## 7.1 Evaluation of the Requirements’ Fulfillment

The implemented BUOS is subsequently compared with the overall and use case requirements for the development of an ICT solution previously identified in chapter 4.2 to identify whether the defined goals have been achieved in this dissertation:

**(OAR1) Definition of mathematical control algorithms**

To enable peak-shaving during peak loads and save energy costs for the companies, the optimal charging and discharging times of the AGV batteries are calculated in the BUOS. The BUOS is a software service in which the algorithms were written in this dissertation. The used algorithms and calculations in the service classes of the BUOS are described in more detail in chapter 5.3.3.

**(OAR2) Relevant object area representation**

This dissertation's relevant object area representation is represented in the concept chapter. A software service is developed for the scheduling of charging and discharging times of the AGV batteries to enable peak shaving in the industrial grids of the companies. The results of chapter 4 show that there was no such a concept and development of other research in this defined relevant object area until the concept and software development of BUOS in this dissertation.

**(OAR3) Real-time interaction with other IT systems**

The BUOS is developed with an MSB interface, which enables the BUOS to react to the events coming from the MSB. It means that the BUOS can receive the data, for example (AGV IDs and company ID) from other IT systems like the AGV software in real-time through MSB and begin to calculate the optimal charging and discharging times for the AGV with the corresponding AGV ID of the manufacturing company with the corresponding company ID. The service instantiation is described in more detail in chapter 5.3.

**(OAR4) Automation of the control system**

The BUOS can autonomously make decisions to control and regulate the charging and discharging times of AGV batteries. The BUOS's decisions are based on the AGV input data like AGV IDs and company ID, which the AGV software sends as an event through the MSB. The BUOS is developed in such a way that it can calculate the charging and discharging times of all AGVs' batteries separately. Then, the calculated charging and discharging times of the AGV batteries are sent to the corresponding AGV software automatically (event-based). The service working procedure is introduced in chapter 5.4.

**(OSR1) Centralized control architecture**

To avoid extensive and time-consuming computations, the BUOS is designed as a central control software that contains three main classes, which work independently and require minimal input data to fulfill their tasks. For example, the available times of the AGV batteries are identified by the "AvailabilityFinder" class. The BUOS communicates to the InfluxDB to read out the data from the AGV measurement. Approximately a half million of data (AGV state) is read by the BUOS from the InfluxDB only once by the "AvailabilityFinder" class to reduce time-consuming computations. Every class has its task and is developed in such a way as to make its own decisions by evaluating only the necessary information available in its environment to avoid extensive and time-consuming computations. The BUOS is main centralized software, which controls and schedules the charging and discharging times of the AGV batteries.

**(OSR2) Dynamical scalability**

The BUOS is developed as a dynamic IT system. It consists of various generic external interfaces to read and write data. It means that in any production system changes, like new users and new production data, the BUOS can get this data without a problem. It also has a modular design. The BUOS software classes are decentralized, and new features can easily be added to the existing BUOS. It can be interpreted that the developed BUOS fulfills the tasks of the dynamical scalability, which is described in the overall requirements.

**(OSR3) Integration into existing production IT landscape**

The BUOS can be easily integrated into different production IT landscapes and hosted in a cloud platform or on-premises, as the BUOS is a dockerized software service programmed in Java. In this dissertation, the BUOS is deployed in the cloud-side platform of the ESP. It runs in a separate VM of the cloud-side platform. A detailed description of the BUOS deployment and other hosting services and databases in the company-side cloud platform can be found in chapter 5.

**(UCR1) Focus on the industrial grid (manufacturing)**

The BUOS can cover the peak loads of the manufacturing companies with the scheduling of discharging times of the AGV batteries. During the BUOS development, industrial grid aspects are considered. For example, the BUOS reads the energy consumption data of a manufacturing company from the InfluxDB to identify the peak load times (see concept chapter 4). The BUOS also requires the company data like electricity cost, peak power cost, and maximum allowed peak power. In this dissertation, the measurement "power" in the BUOS MySQL data model is designed and implemented in MySQL so that the BUOS can get the critical company data to calculate the optimal charging and discharging times of the AGV batteries.

**(UCR2) Electricity cost and peak load reduction**

Only the peak shaving of the DR options is considered in this dissertation. The BUOS is developed in such a way as to enable peak shaving in the companies with the AGV batteries so that the electricity cost of the same manufacturing company can be reduced. The implemented measurements of the DBs are introduced in the description of the previous requirement.

**(UCR3) Usage of the AGV batteries**

The KUKA AGVs with lithium batteries, whose features have been adopted in various simulations for the CMUC and PMUC, and BMUC AGVs are used as AGV batteries in this dissertation. In addition, the BUOS is programmed to create the battery aging function according to the cycle aging of lithium batteries. The lithium battery feature variables of the

AGVs were also uploaded to the BUOS to be used when calculating the cost savings. BUOS was developed so that the AGV batteries were only scheduled during idle and charging times. The working times were not considered in calculating the optimal charging and discharging times of the AGV batteries by the BUOS. Furthermore, the focus is placed on that the AGVs can perform their tasks in production without disturbance. It means that the AGV batteries can be charged and discharged only during the available and idle times of the AGVs. Additionally, the BUOS and the developed simulation for the use cases allow only one AGV to be connected to one charging station. After an AGV is connected to a charging station, the charging station status is set to unavailable.

**(UCR4) Optimization of the AGVs' batteries charging schedule**

Only AGVs with lithium battery technology were considered in this dissertation. The BUOS calculates optimal discharge and charge times only when the SOC of AGV batteries is between predefined values of 20-90 % because the SOC of all AGVs should remain between 20 and 90 % so that the batteries can be conserved. These limits were also considered in the simulation development for different use cases. The AGVs are constantly driven to a charging station with a SOC value under 20 %. After the SOC value reached 90 %, they went off again to complete their transportation tasks. The AGV battery charging and discharging times did not negatively affect the existing production plan.

**(UCR5) Service development as an ICT solution**

The BUOS is developed as a generic service (ICT solution) for all AGV battery charging methods and schemes. This is described in chapter 5.1 in more detail. The BUOS is programmed in Java and consists of different external interfaces to communicate with other IT systems and DBs. It is also dockerized to be hosted in the different cloud or edge platforms. In this dissertation, the digital implementation of BUOS is described and validated theoretically. In future works, the hardware implementation of this approach can be realized.

**(UCR6) Running ICT solution in a company platform**

The BUOS can run on all different cloud and edge platforms. This dissertation used the company-side platform of ESP (Schel et al. 2018b, p. 181) as a company platform. The company platform was required for different IT systems' data storage and execution. The hardware of a required data center of ESP was available so that the company platform and MSB could be used to validate the BUOS to calculate the cost savings of three different companies from the use cases. InfluxDB and MySQL were launched in a VM of this platform to store the data. Additionally, the BUOS is deployed in a separate VM of this platform. Moreover, MSB is also hosted in another separate VM, so services such as the BUOS, the AGV software, and the DB adapter can exchange data. Finally, the firewalls of the VMs are set so that the BUOS can communicate with the DBs and other IT systems.

**(UCR7) Consideration of renewable systems**

Renewable systems are considered in this dissertation. The companies sent renewable energy data in Excel files. They were stored in the InfluxDB of the company platform. The BUOS used this data to find out the peak load times of the companies. Using this data in the BUOS algorithms is presented in more detail in chapter 5.3.3.

**(UCR8) Bidirectional communication interface**

The AGVs, the charging stations, and renewable energy resources should work as the CPS (consisting of connectors to the company platform) to gather data from the AGVs, the charging stations, and renewable energy resources and store them in the company platform. The BUOS is developed with an MSB interface to communicate with other IT systems in the MSB and exchange its data. Moreover, The DBs, which are used in this dissertation, had external interfaces. The interface tests of these DBs are shown in chapter 5.5. The results indicate that the data can be written to these DBs and read from these DBs by the BUOS.

Moreover, the AGVs, charging stations, renewable energy sources, and production facilities (working stations) should contain a bidirectional, IP-capable, and push-capable communication interface and be able to transfer their data to a DB in a company platform. The companies considered in this dissertation do not possess any AGVs, charging stations, or renewable energy resources. Therefore, a simulation model was developed to create this data. The created data is uploaded to the DBs of the company platform through the DB connectors via REST interfaces.

## 7.2 Answering the Research Questions

The objective of this dissertation is achieved when the main research question can be fully answered and a well-grounded proof of results is available. Based on the main research question - ***How should an algorithm-based ICT solution be designed to realize energy flexibility in manufacturing with peak shaving load control using AGV lithium batteries to enable cost savings for the companies during peak loads*** -five sub-research questions were derived, which provide the answer to the main research question. These have already been answered systematically and comprehensively in the preceding chapters:

1. What are the already developed concepts and approaches with battery technologies to realize energy flexibility in manufacturing using load-control method peak shaving, and what are the challenges of using AGV lithium batteries as energy storage compared to these existing concepts and approaches?

Different concepts and approaches with battery technologies were developed to realize energy flexibility in manufacturing using the load-control method of peak shaving. In chapter 3.1, 12 papers with stationary batteries, three papers with EV batteries, and five papers with AGV batteries of the researchers were introduced, aiming to enable peak shaving on the power grid. Then, these existing works were compared to the defined requirements of this dissertation. Although the multiple AGVs compared to the number of stationary batteries exist in a manufacturing company, they face a challenge in that the AGV batteries are not available at all times compared to the stationary batteries so that they can be charged and discharged in peak load times, because they have production schedule and trip distance (logistic tasks) dependency. This challenge is considered during the development of the BUOS. Comparing the requirements with the existing research approaches shows that reducing peak loads in an industrial grid with AGV batteries has yet to be the focus of the research.

2. What are the essential requirements to develop this solution for the AGV lithium batteries?

The essential overall and use case requirements were described in chapter 4.2 to answer this research question. The requirements are categorized into two different groups. First, the overall requirements are identified to describe which criteria must be met to develop and implement a generic service that is suitable to be used by industrial companies. Then, the use case requirements are introduced for the BUOS to realize energy flexibility in manufacturing with peak shaving load control using AGV lithium batteries.

3. How should the algorithm-based ICT solution be developed to provide power cost savings and peak shaving in a manufacturing company while using AGV lithium batteries as energy storage?

Chapter 4.3 describes the concept of the BUOS design and algorithm. In chapter 5.3, the BUOS development was indicated in more detail. The BUOS is a dockerized software service programmed in Java, which consists of external interfaces like MSB interface and DBs' interfaces to provide bidirectional communication with external IT systems.

4. How to validate whether any economic advantage is gained by using AGV lithium batteries to cover peak loads for the manufacturing companies?

The selected validation method for the BUOS was described in chapter 4.4. First, requirements are identified to select a validation method. Then, these requirements are compared to existing calculation models according to state of the art to find the suitable validation method. The sensitivity analysis was selected based on the comparison results to validate the BUOS. This selection was to check the reaction of the output variable (cost savings) with the adjusted input variables. This determined whether this approach (BUOS software) is cost-effective, when and with which changed input variables will become even more cost-effective for the companies.

5. How cost-effective is it for a manufacturing company to use AGVs along with this solution as energy storage and transport systems?

The validation results are introduced in chapter 6. The results indicate that the companies considered in this dissertation can benefit from using BUOS in peak load times and make a minimal profit. However, these companies are not recommended to buy additional new

AGVs to reduce peak loads. The existing AGVs can be used in idle times as energy storage for the companies.

# 8 Summary and Outlook

Manufacturing companies are currently dealing with a complex environment for their factories concerning current and future energy supply. The companies should pay electricity costs based on two readings. One is for the manufacturing company's energy consumption, and the other is for peak demand. The electricity suppliers contractually arrange pricing models with the companies based on the highest peak production load. Manufacturing companies face these load peaks in their manufacturing and pay high amounts of money because of the generation of peak loads.

Various battery utilization research applications and concepts have been developed to enable peak load reduction in production facilities. The researchers investigated the peak shaving opportunities with the stationary, EV batteries in the industrial grid.

This dissertation aims to enable peak shaving and reduce electricity costs in manufacturing companies with AGV lithium batteries through an algorithm-based ICT solution. First, a generic approach concept with overall and use case requirements was presented. Then the development of the BUOS was introduced. Last, the potential of using AGVs as energy storage to reduce peak loads in a manufacturing company was illustrated after a sensitivity analysis was performed with the calculated results by the BUOS in three different use case scenarios.

The sensitivity analysis results show that the AGV battery capacity has a minor influence on cost savings. In addition, increasing the AGV amount and peak electricity costs have a linear relationship with cost savings. In summary, using AGV batteries as energy storage to minimize peak loads can benefit manufacturing companies that utilize large AGV fleets in their logistics processes. For the manufacturing companies considered in this dissertation, it is recommended to use BUOS to reduce their peak electricity costs. Still, it is not cost-effective for these companies to procure new AGVs to reduce peak loads.

In future work, the developed service can be used in different manufacturing companies to validate the economic viability of the developed solution approach. In addition, it is recommended to develop the BUOS to investigate further whether it is economical to reduce electricity costs of manufacturing companies by trading electricity in the intraday market with the help of AGV batteries.

In this dissertation, only the theoretical implementation is considered and described. It can also be interesting to research how this approach can be implemented so that the AGVs can discharge their batteries at the charging stations to support the industrial power grid of the manufacturing companies during the peak loads. In addition, it can also be investigated how stationary EV batteries can be implemented together with the AGV batteries in a manufacturing company so that the companies can profit the most.

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# Appendix

## A. BUOS Code

To run the BUOS code, the Docker file, BUOS code (jar-File), and Docker-Compose file are required and should be downloaded. These files can be found at the link (https://synergie.bscw.de/sec/bscw.cgi/21957). The following steps should be applied to execute the BUOS code:

1. The Docker settings (see chapter 0) should be adjusted in the Dockerfile. You can configure the settings for MySQL database, InfluxDB, and MSB here.
2. The second step is to prepare the Docker-Compose file (docker-compose.yml) (see 0). If new services are to run via Docker, the configurations of these services can be added to this file in the future.
3. WinSCP software is required in this step. After installing WinSCP software, you can save the BUOS code and BUOS docker file in the VM of the company-side platform.
4. In this step, putty software is needed. With this software, you can connect to the VM of the company platform. First, you must find the folder where the Docker-Compose file is located. Then, the following command must be inserted in the terminal to run the BUOS in the VM:

   **$ sudo docker-compose up –d**

Additionally, the BUOS source code can be found in the CodeBeamer repository and cloned from this registry (https://cb.ipa.fraunhofer.de/cb/git/BUOS_Backend).

## A1. Docker File

```
FROM openjdk:11.0.4-jre
MAINTAINER Ozan Yesilyurt (ozan.yesilyurt@ipa.fraunhofer.de)

ENV JAR_FILE_NAME="BUOS.Backend-0.1.0-SNAPSHOT.jar"
ENV SERVER_INSTALL_FOLDER="/jar_code/"

ENV DATABASE_HOST=mysql
ENV DATABASE_PORT=3306
ENV DATABASE_SCHEMA="buos_repository"
ENV DATABASE_USERNAME="root"
ENV DATABASE_PASSWORD="password"

# ENV MSB_URL="https://ws.msb.sng.cell.vfk.fraunhofer.de"
ENV MSB_URL="ws://10.3.30.20:8085"
ENV MSB_UUID="9d43a822-a4a5-11ea-bb37-0242ac130002"
ENV MSB_NAME="BEOS Service"
ENV MSB_DESCRIPTION="Batterieeinsatzoptimierungsservice"
ENV MSB_TOKEN="0242ac130002"
ENV MSB_TRUSTSTORE="./cert/CERTS.trs"

ENV INFLUXDB_DATABASEURL: "http://10.3.30.138:8086"
ENV USERNAME: "root"
ENV PASSWORD: "password"
ENV DBNAME: "BUOS"

RUN mkdir -p ${SERVER_INSTALL_FOLDER}log

ADD ${SERVER_INSTALL_FOLDER}${JAR_FILE_NAME}
${SERVER_INSTALL_FOLDER}${JAR_FILE_NAME}

CMD java -jar -Xmx1024m -Xms512m ${SERVER_INSTALL_FOLDER}${JAR_FILE_NAME}
```

## A2. Docker-Compose File

```
version: '3'
services:
   portainer:
      image: "portainer/portainer"
      container_name: portainer
      logging:
        driver: "json-file"
        options:
          max-size: "1m"
          max-file: "1"
      ports:
        - "9000:9000"
      volumes:
        - /var/run/docker.sock:/var/run/docker.sock
      restart: always
   beos:
      container_name: beos
      networks:
        beos:
          aliases:
            - beos
      ports:
         - 4040:4040
      environment:
        DATABASE_HOST: 10.3.30.140
        DATABASE_PORT: 3306
        DATABASE_SCHEMA: "buos_repository"
        DATABASE_USERNAME: "root"
        DATABASE_PASSWORD: "password"
      build:
         context: BEOS_Backend
      restart: always
   db:
    container_name: mysql
    image: mysql:5.7
    restart: always
    networks:
      beos:
        aliases:
          - db
    environment:
      MYSQL_DATABASE: 'buos_repository'
      # MYSQL_USER: 'root'
      # MYSQL_PASSWORD: 'password'
      # Password for root access
      MYSQL_ROOT_PASSWORD: 'password'
    ports:
      # <Port exposed> : < MySQL Port running inside container>
      - '3306:3306'

networks:
  beos:
```

## B. BUOS Execution Tests' Results

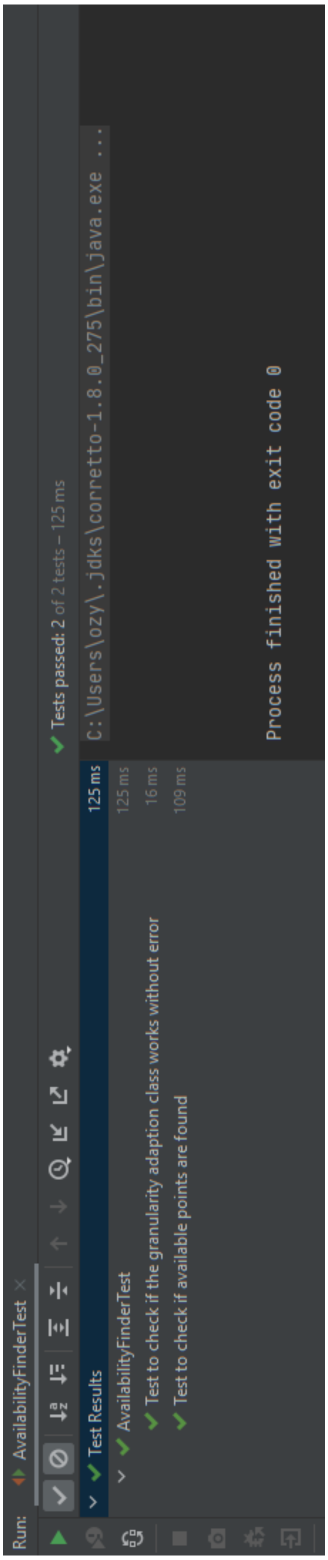


Figure B.1: AvailabilityFinder Class Unit Test Results

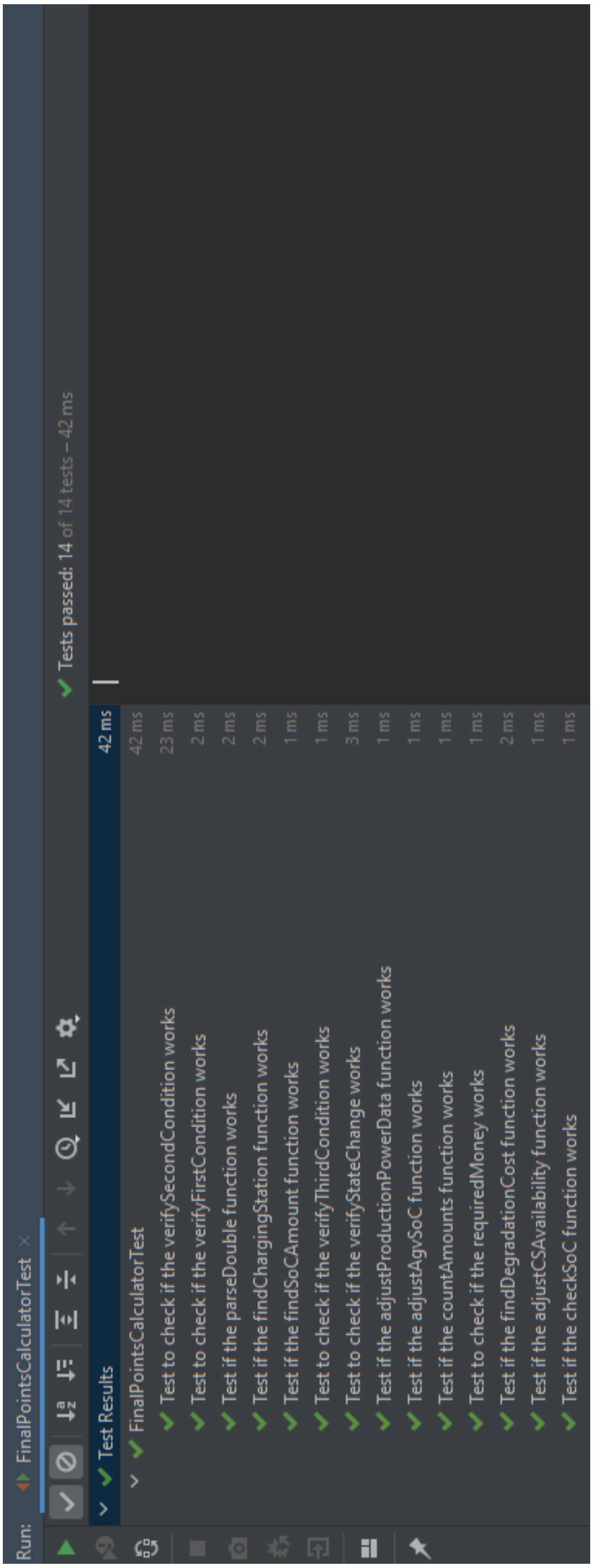


Figure B.2: FinalPointsCalculator Class Unit Test Results

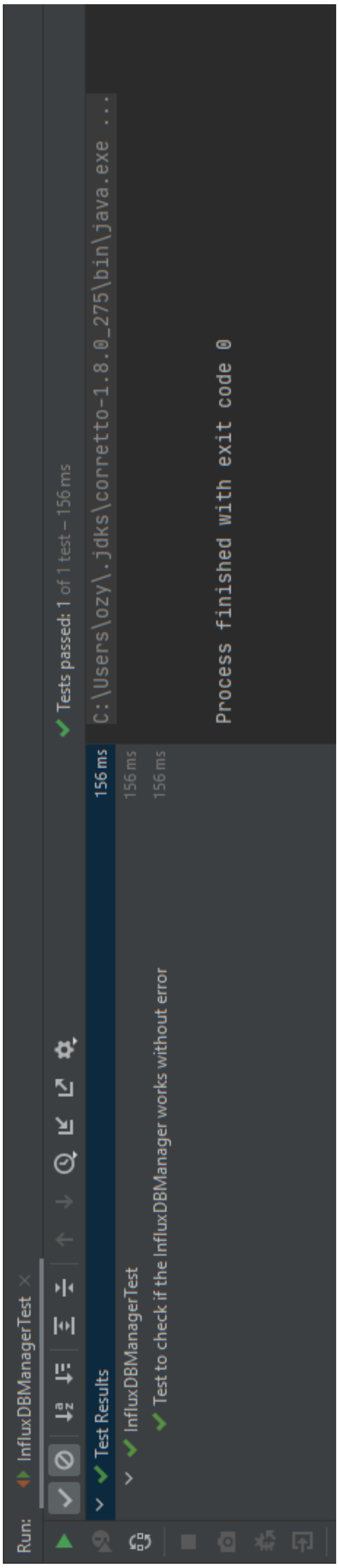


Figure B.3: InfluxDBManager Class Unit Test Results

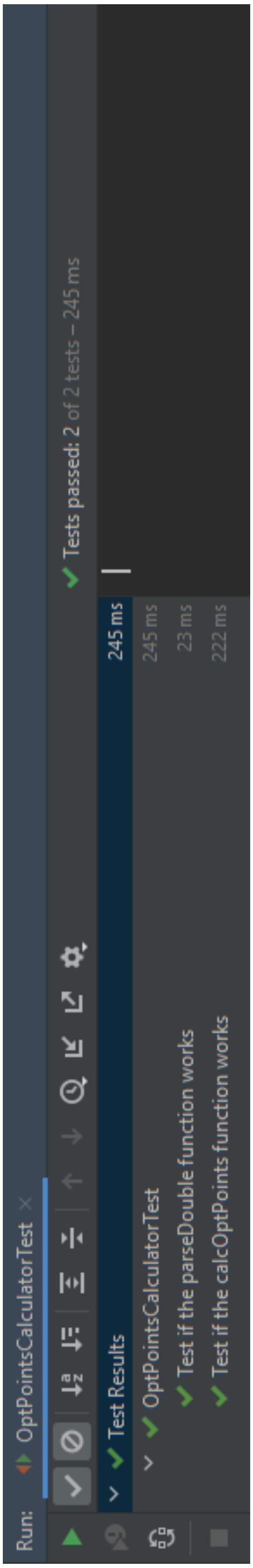


Figure B.4: OptPointsCalculator Class Unit Test Results

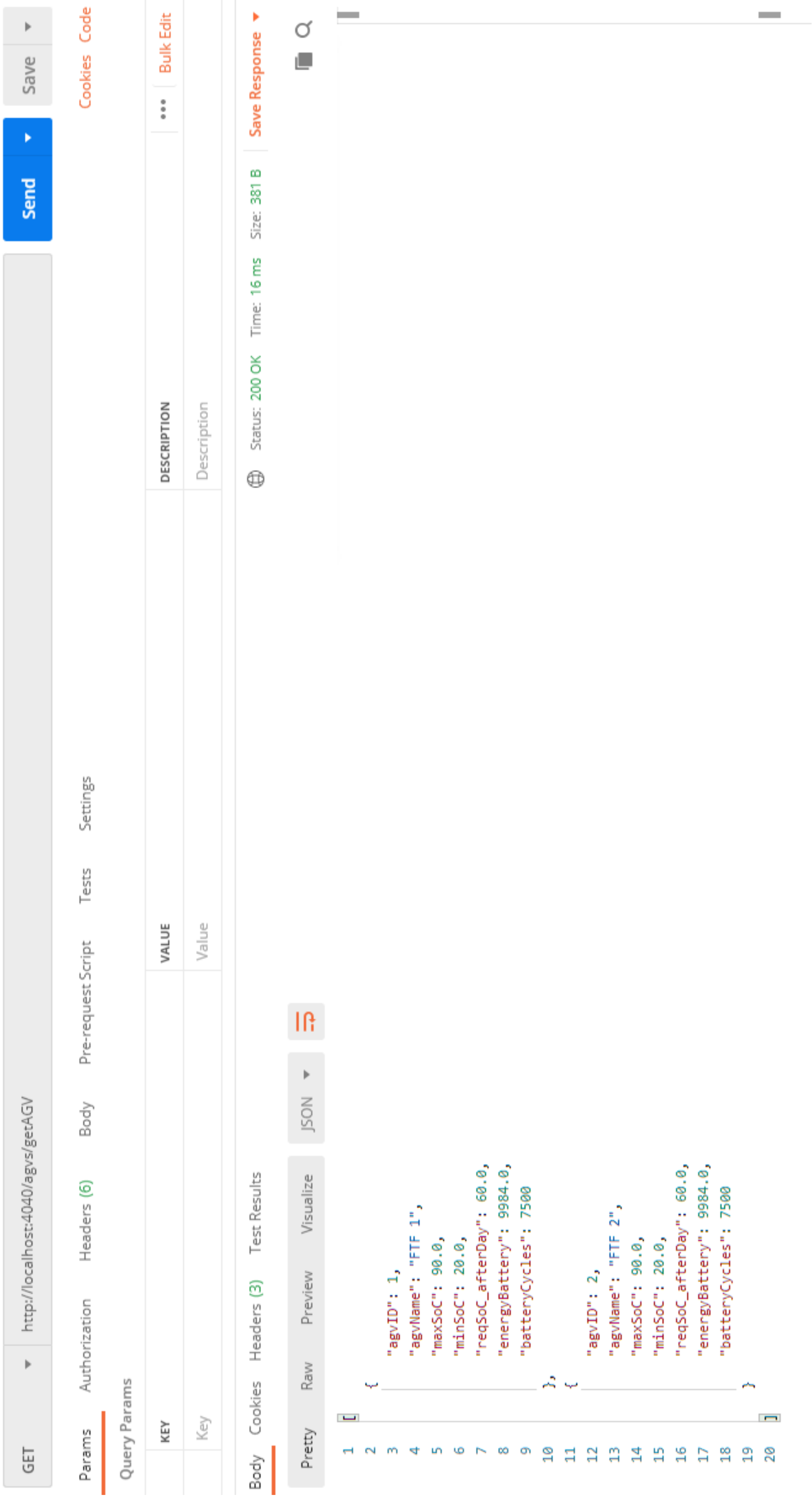


Figure B.5: BUOS REST interface test with GET method

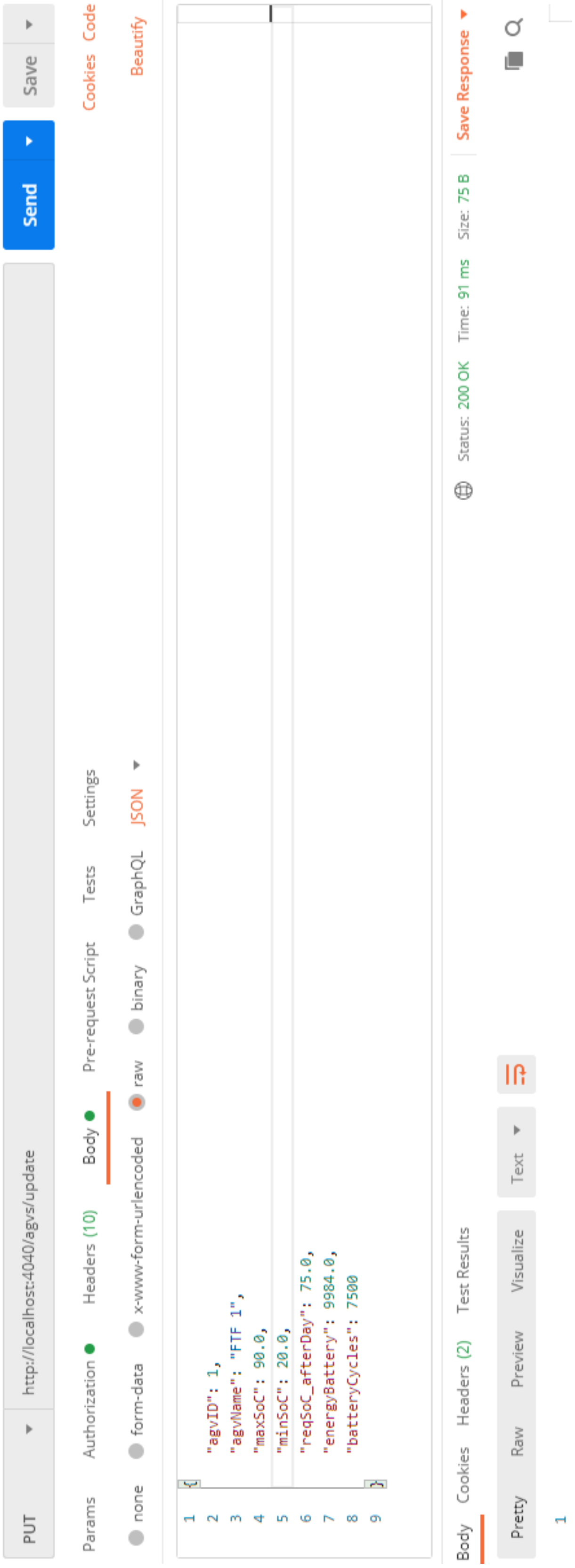


Figure B.6: BUOS REST interface test with PUT method

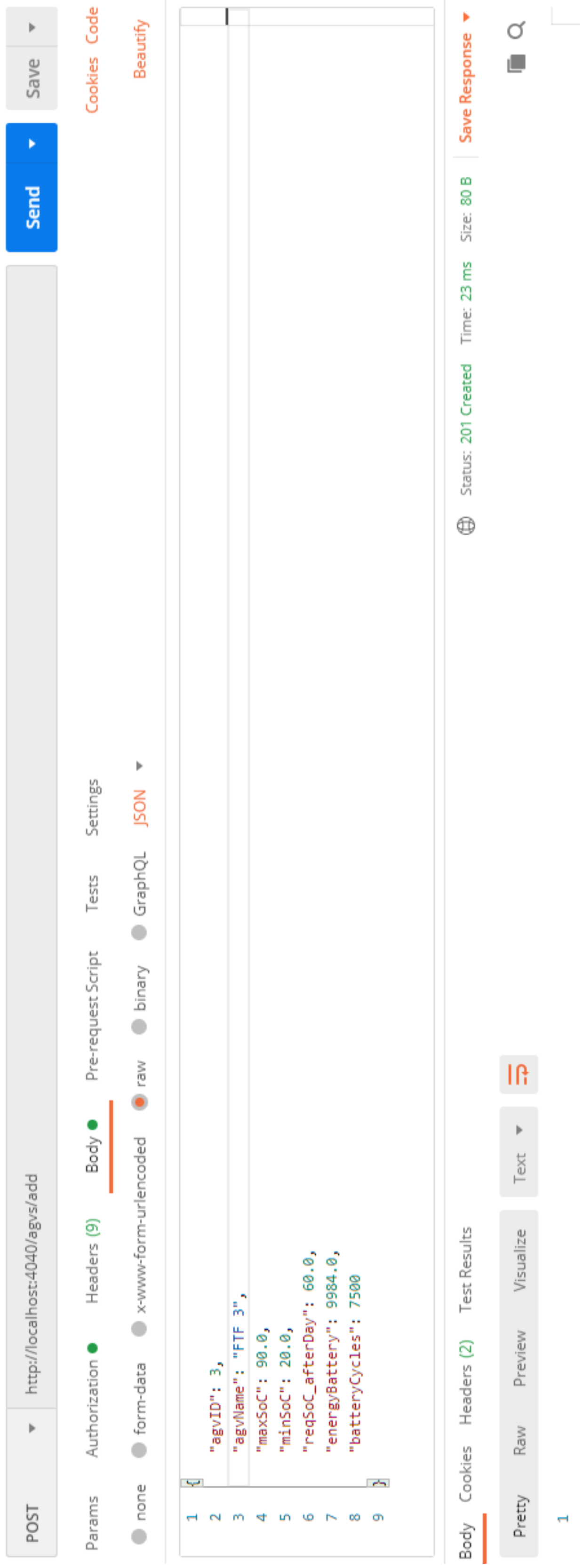


Figure B.7: BUOS REST interface test with POST method

## C. Use Case Scenario's Simulation Data

| | string 0 | time 1 | integer 2 | string 3 | integer 4 |
|---|---|---|---|---|---|
| string | Identifier | CurrentTime | csID | Measurement | csAvailability |
| 1 | 1 | 1:00.0000 | 1 | ChargingStation | 1 |
| 2 | 2 | 2:00.0000 | 1 | ChargingStation | 1 |
| 3 | 3 | 3:00.0000 | 1 | ChargingStation | 1 |
| 4 | 4 | 4:00.0000 | 1 | ChargingStation | 1 |
| 5 | 5 | 5:00.0000 | 1 | ChargingStation | 1 |
| 6 | 6 | 6:00.0000 | 1 | ChargingStation | 1 |
| 7 | 7 | 7:00.0000 | 1 | ChargingStation | 1 |
| 8 | 8 | 8:00.0000 | 1 | ChargingStation | 1 |
| 9 | 9 | 9:00.0000 | 1 | ChargingStation | 1 |
| 10 | 10 | 10:00.0000 | 1 | ChargingStation | 1 |
| 11 | 11 | 11:00.0000 | 1 | ChargingStation | 1 |
| 12 | 12 | 12:00.0000 | 1 | ChargingStation | 1 |
| 13 | 13 | 13:00.0000 | 1 | ChargingStation | 1 |
| 14 | 14 | 14:00.0000 | 1 | ChargingStation | 1 |
| 15 | 15 | 15:00.0000 | 1 | ChargingStation | 1 |
| 16 | 16 | 16:00.0000 | 1 | ChargingStation | 1 |
| 17 | 17 | 17:00.0000 | 1 | ChargingStation | 1 |
| 18 | 18 | 18:00.0000 | 1 | ChargingStation | 1 |
| 19 | 19 | 19:00.0000 | 1 | ChargingStation | 1 |
| 20 | 20 | 20:00.0000 | 1 | ChargingStation | 1 |
| 21 | 21 | 21:00.0000 | 1 | ChargingStation | 1 |
| 22 | 22 | 22:00.0000 | 1 | ChargingStation | 1 |
| 23 | 23 | 23:00.0000 | 1 | ChargingStation | 1 |
| 24 | 24 | 24:00.0000 | 1 | ChargingStation | 1 |
| 25 | 25 | 25:00.0000 | 1 | ChargingStation | 1 |
| 26 | 26 | 26:00.0000 | 1 | ChargingStation | 1 |

Figure C.1: Charging station simulation data from the Plant Simulation

| | string<br>0 | time<br>1 | integer<br>2 | string<br>3 | integer<br>4 | real<br>5 | real<br>6 | real<br>7 | real<br>8 |
|---|---|---|---|---|---|---|---|---|---|
| string | Identifier | CurrentTime | agvID | Measurement | agvAvailability | socAGV | agvLatPosition | agvLngPosition | velocityAGV |
| 1 | 1 | 1:00.0000 | 1 | AGV | 0 | 49.88 | 0.80 | 2.00 | 1.00 |
| 2 | 2 | 2:00.0000 | 1 | AGV | 0 | 49.82 | 0.80 | 2.00 | 1.00 |
| 3 | 3 | 3:00.0000 | 1 | AGV | 0 | 49.76 | 0.80 | 2.00 | 1.00 |
| 4 | 4 | 4:00.0000 | 1 | AGV | 0 | 49.69 | 0.80 | 2.00 | 1.00 |
| 5 | 5 | 5:00.0000 | 1 | AGV | 0 | 49.63 | 0.80 | 2.00 | 1.00 |
| 6 | 6 | 6:00.0000 | 1 | AGV | 0 | 49.56 | 0.80 | 2.00 | 1.00 |
| 7 | 7 | 7:00.0000 | 1 | AGV | 0 | 49.50 | 0.80 | 2.00 | 1.00 |
| 8 | 8 | 8:00.0000 | 1 | AGV | 0 | 49.44 | 0.80 | 2.00 | 1.00 |
| 9 | 9 | 9:00.0000 | 1 | AGV | 2 | 49.28 | 24.20 | 2.00 | 1.00 |
| 10 | 10 | 10:00.0000 | 1 | AGV | 0 | 49.20 | 27.20 | 2.00 | 1.00 |
| 11 | 11 | 11:00.0000 | 1 | AGV | 0 | 49.14 | 27.20 | 2.00 | 1.00 |
| 12 | 12 | 12:00.0000 | 1 | AGV | 0 | 49.07 | 27.20 | 2.00 | 1.00 |
| 13 | 13 | 13:00.0000 | 1 | AGV | 0 | 49.01 | 27.20 | 2.00 | 1.00 |
| 14 | 14 | 14:00.0000 | 1 | AGV | 0 | 48.95 | 27.20 | 2.00 | 1.00 |
| 15 | 15 | 15:00.0000 | 1 | AGV | 0 | 48.88 | 27.20 | 2.00 | 1.00 |
| 16 | 16 | 16:00.0000 | 1 | AGV | 0 | 48.82 | 27.20 | 2.00 | 1.00 |
| 17 | 17 | 17:00.0000 | 1 | AGV | 2 | 48.66 | 24.20 | 2.00 | 1.00 |
| 18 | 18 | 18:00.0000 | 1 | AGV | 0 | 48.59 | 27.20 | 2.00 | 1.00 |
| 19 | 19 | 19:00.0000 | 1 | AGV | 0 | 48.52 | 27.20 | 2.00 | 1.00 |
| 20 | 20 | 20:00.0000 | 1 | AGV | 0 | 48.46 | 27.20 | 2.00 | 1.00 |
| 21 | 21 | 21:00.0000 | 1 | AGV | 0 | 48.39 | 27.20 | 2.00 | 1.00 |
| 22 | 22 | 22:00.0000 | 1 | AGV | 0 | 48.33 | 27.20 | 2.00 | 1.00 |
| 23 | 23 | 23:00.0000 | 1 | AGV | 0 | 48.27 | 27.20 | 2.00 | 1.00 |
| 24 | 24 | 24:00.0000 | 1 | AGV | 0 | 48.20 | 27.20 | 2.00 | 1.00 |
| 25 | 25 | 25:00.0000 | 1 | AGV | 2 | 48.04 | 24.20 | 2.00 | 1.00 |
| 26 | 26 | 26:00.0000 | 1 | AGV | 0 | 47.97 | 27.20 | 2.00 | 1.00 |

Figure C.2: AGV simulation data from the Plant Simulation