

## DOCTOR OF PHILOSOPHY

### **An approach to potential evaluation of a contactless energy supply infrastructure for occasional recharging in production related, non-automated material handling**

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**An approach to potential evaluation of a contactless  
energy supply infrastructure for occasional recharging  
in production related, non-automated material handling**

by

**Patrick Laszlo Fekete**

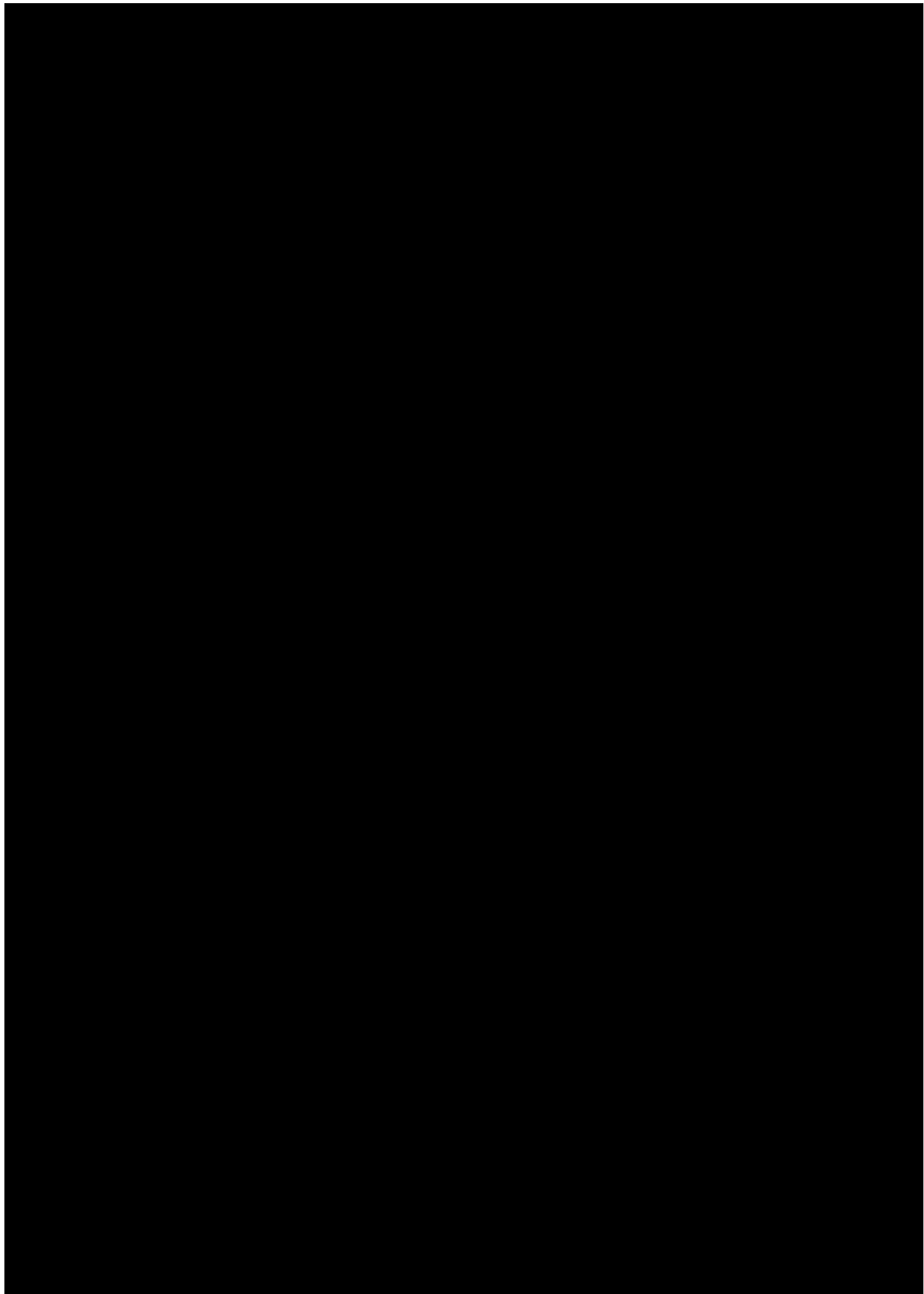
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**ABSTRACT**

**Key words:** Process energy monitoring, Occasional electric vehicle charging, Maximal covering location modelling, Energy efficient charging station allocation

Significant advances have been made in the research and development of electric vehicles (EV's). Along with the major challenge of energy storage, being also addressed is the efficient design of system energy transfer and consumption. This has had the effect of fundamentally changing perspectives across the mobility and transportation sector. Applied predominantly to road-going vehicles, the industrial context of non-road Electric Vehicles (nrEV's) and specifically the use of manned electric forklift trucks integrated within the production related materials handling system has, to-date, received far less attention.

The overarching aim of this research is to examine the impact and potential for the use of contactless occasional recharging of nrEV's integrated within a manufacturing line, recognising the need to balance the (sometimes competing) demands of delivering sustainable production while exercising environmental responsibility.

Meeting the objectives of this research resulted in the development of a location-allocation model for electric charging station determination based on a fundamental understanding of the nature and quality of process inherent key performance indicators (KPI's) as well as comprehensive process and energy monitoring while considering both Lean and Green Management perspectives. The integration of the generated knowledge and information into a generally valid simulation tool for occasional charging system implementation allows to more thoroughly investigate the impact from occasional charging to overall efficiency and sustainability to be realised.

An investigation into relevant literature identified the need for specifically generated energy consumption data and confirmed the need for an energy optimisation model specific to the area of production related materials handling. Empirical data collected from repeated standardised materials handling operations within a selected production related materials handling environment resulted in the development of the Standard Energy Consumption Activity tool (SECA). Further work within this pilot study confirmed the tool as capable of generating reliable and valid data and confirmed the SECA tool as a generally applicable benchmark for

energy consumption determination in material handling based on fractional process functions.

Integrating this approach into a comprehensive process analysis and charging infrastructure optimisation resulted in the development of an Excel-based simulation model. The (Occasional Charging Station Location Model) OCSLM is based upon Maximal Covering Location Modelling and an endogenous covering distance definition in order to simulate process related potentials and optimal charging system implementation allocations, the target being to increase vehicles usable battery energy.

A comprehensive case study based upon six individual and one combined data set confirmed the general and wider applicability of the OCSLM model while the application of the model provides a set of novel results. The application demonstrated a theoretical increase in usable battery energy of between 40% and 60% and within the same case study the impact of technology implementation identified that a reduction in battery and system cost of between 5% and 45% can be realised. However, the use of contactless power transfer resulted in an increase in CO<sub>2</sub> emissions of up to 6.89% revealing a negative impact to overall ecology from the use of this energy transfer system.

Depending on the availability of fast connecting, contact based energy transmission systems, the approach and results of OCSLM have shown to be directly applicable to contact based systems with resulting CO<sub>2</sub> emissions decreasing by 0.94% at an energy transfer efficiency of 96%.

Further novelty, of benefit to both academic and industry practice, was realised through the framework and information of the research with the provision of SECA as a process function-based and generally applicable energy consumption standard, OCSLM as a Maximal Covering Location Modell with a focus on occasional charging based on an endogenous covering distance and integrating detailed energy and process monitoring into electric charging station allocation, and the methodology for the application of this approach for fast connecting contactless and contact charging models and cases.

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**LIST OF PUBLICATIONS**

1. Fekete, P., Martin, S., Kuhn, K. and Wright, N. (2014) 'The status of energy monitoring in science and industry by the example of material handling processes'. *Business, Management and Education* (12), 213-227
2. Fekete, P., Martin, S., Kuhn, K. and Wright, N. (2015) 'Kontaktlose Energieübertragung im produktionsbezogenen Warentransport – Prozess- und Standardverbrauchsanalysen als Grundlage zur Bewertung von Integrationspotentialen'. *Horizonte* (45), 14-16
3. Fekete, P., Lim, S., Martin, S., Kuhn, K. and Wright, N. (2015) 'Combined energy and process simulation to foster efficiency in non-automated material handling system design'. *Studies in Engineering and Technology* (3), 28-39
4. Fekete, P. and Martin, S. (2016) *An approach to potential evaluation of contactless energy supply infrastructure for occasional recharging in production related, non-automated material handling*. Unpublished poster presentation at 'CU Research Symposium'. Held 24 February 2016 at Coventry University
5. Fekete, P. (2016) *Energie und ihre Potentiale im intralogistischen Materialfluss – am Beispiel kontaktloser Gelegenheitsladung. Energy and its potentials within intralogistic material handling – by the example of contactless occasional charging.* '14. Loerracher Logistik Forum – Innovationen in Logistiktechnik und Logistikmanagement'. Presentation, held 22 April 2016. Loerrach, Germany
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**DECLARATION**

I hereby declare that this thesis with the title ‘An approach to potential evaluation of contactless energy supply infrastructure for occasional recharging in production related, non-automated material handling’ is my own work and effort. All sections of the text and results that have been obtained from other sources are fully referenced. The research project was conducted between September 2013 and September 2016 in the Mechanical, Automotive and Manufacturing Engineering Department of the Faculty of Engineering and Computing at Coventry University. The thesis has not been submitted in whole or in part as consideration of any other degree or qualification at this university or any other institute of learning.



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Date



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**LIST OF NOMENCLATURE**

<b>Abbreviation</b>	<b>Description</b>	<b>Unit</b>
$a^*$	maximum distance of demand and supply	m
$b_r$	demand in location r	-
$C_r$	roll resistance coefficient	-
$C_{bat}$	battery capacity	kWh
$d_r$	distance from demand spot r to facility allocation	m
$E_{aux}$	auxiliary energy	kWh
$E_{calc}$	energy consumption measured	kWh
$E_{cw}$	process energy	kWh
$E_D$	energy consumption planar movement	kWh/m
$E_{fr}$	friction energy losses	Nm
$E_{kin}$	kinetic energy	Nm
$E_L$	energy consumption vertical movement	kWh/0,1m
$E_{meas}$	energy consumption measured	kWh
$E_{pot}$	potential energy	Nm
$E_t$	target energy	kWh
$F_N$	axial force	N
$g$	gravity acceleration	m/s <sup>2</sup>
$h$	height	m
$i$	current	ampere
$i$	break time allocation spot	(x / y)
$I$	number of break time allocations	-
$j$	facility allocation spot	(x / y)
$J$	number of possible facility locations	-
$m$	mass	kg
$r$	demand spot	-
$s$	drive distance	m
$S$	set of available facilities	-
$\Delta t$	time difference	s
$u$	voltage	volt
$v$	velocity	m/s
$W_E$	working energy – SECA	kWh/unit
$x_{rj}$	binary variable for demand attribution	-
$X$	number of facilities that cover defined demand	-
$z_r$	binary variable if demand is covered	-
$Z$	demand coverage	-
<b>For CFRLM</b>		
$a_{hk}$	binary variable of a facility to be part of h	-
$b_{qh}$	binary variable of the capability to refuel O-D pair q	-
$f_q$	flow volume of origin-destination pair	-
$H$	set of all potential facility combinations	-
$K$	sum of all possible facility locations	-
$x_k$	binary variable of facility to be located in k	-
$v_h$	binary variable for facilities to be opened	-
$Y_q$	binary variable if demand located on O-D route	-

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<b>For GCM</b>		
$w_i$	weighting factor to facility allocation	-
$R$	coverage radii	m
<b>For OLSCM</b>		
$n$	number of refuelling operations	-
$r_{jk}$	level of coverage	-
$s_k$	number of supply points	-
$u$	number of chargers	-
$x_{jk}$	proportion of users from demand sport $j$	%
$y_k$	binary variable for charging station being located in $k$	-
$z_k$	capacity for recharging of a facility in $k$	kWh
<b>For SOMCI</b>		
$A_j$	binary variable for the allocation of a type- $g$ charger	-
$f_j$	amount of recharged energy	kWh
$G$	number of available charging technologies	-
$h_j$	number of chargers in $j$	-
$N_{v,j}$	number of vehicle approaches to $j$	-
$R$	charging rate	kW
$V$	number of EV	-
<b>For OCSLM</b>		
$a_i$	demand in point $i$	kWh
$C$	number of sites	-
$d_{ij}$	distance from $i$ to $j$	m
$\eta_j$	transmission efficiency	%
$E_{ij}$	additional energy input from demand spot $i$ in $j$	kWh
$h_j$	characteristics of charging facility	kWh
$N_i$	set of stations for demand coverage	-
$p_t$	performance of energy transmission	kW
$q_i$	quality of demand	s
$S_{ij}$	binary variable for efficiency evaluation of $E_{ij}$	-
$t_{dij}$	driving time form $i$ to $j$	s
$t_i$	usable break time in $i$	s
$x_j$	binary variable for energy efficient integration of $a_i$	-

**LIST OF ABBREVIATIONS**

AFV	Alternative Fuel Vehicle
BEV	Battery Electric Vehicle
CFRLM	Capacitated Flow Refuelling Location Model
CPT	Contactless Power Transfer
CSCM	Charging Station Covering Model
CSR	Corporate Social Responsibility
DoD	Depth of Discharge
EREV	Extended Range Electric Vehicle
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FCV	Fuel Cell Vehicle
GCM	Gradual Cover Model
GHG	Greenhouse Gas
GM	Green Management
h	hours
kg	kilogram
KPI	Key Performance Indicator
kW	kilowatt
kWh	kilowatt hours
LM	Lean Management
LSCM	Location Set Covering Model
m	metres
MCLM	Maximal Covering Location Model
MH	Material Handling
MHC	Material Handling Component
MHP	Material Handling Process
Mt	Million tonnes
nrEV	Non-road Electric Vehicle



OCSLM	Occasional Charging Station Location Model
O-D	origin-destination
OLCSM	Optimal Location of Charging Stations Model
PHEV	Plug-in Hybrid Electric Vehicle
rEV	Road Electric Vehicle
RP	Research Phase
s	seconds
s.c.	side condition
SECA	Standardised Energy Consuming Activity
SI	Système international d'unités
SOMCI	Simulation-Optimisation Model for Charging Infrastructure
sSCM	Sustainable Supply Chain Management
UBE	Usable Battery Energy
VMT	Vehicle Miles Travelled
WPT	Wireless Power Transfer

---

# CHAPTER 1

## INTRODUCTION

‘All economic sectors must take steps to reduce their energy consumption, particularly where there is still significant energy efficiency potential and where quick wins are possible, in particular the transport and buildings sector’ (Šefčovič 2014). ‘By reducing our energy demand, and better managing our supply [...] we are delivering on our promise and enhancing the stability of Europe’s energy market’ (Šefčovič 2015).

In accordance with these statements by Maroš Šefčovič, Vice President of the European Energy Commission, and his request for improved energy usage, the pursued research project shall seek to examine the influence from the integration of an electricity supply infrastructure for occasional battery charging to industrial material handling systems. In order to address the demand for increased energy efficiency, the research investigates the potential for increased energy availability as well as the impact from technology implementation to economic and ecologic sustainability of the transportation system in reference to an optimised charging infrastructure allocation.

Global mega trends such as increasing populations and welfare, improved communication and digitalisation, new mobility and transportation systems as well as the ongoing globalisation increases the demand for products, energy and resources (Kartnig, Grösel and Zrnica 2012). Reacting to these developments as well as to increased price sensitivity of customers, industrial entities base their production strategies on high standardisation and mass production in order to increase their outputs and by this economic growth (Retief 2016). Conversely to the described developments, new consumption patterns and increased customers demand for higher levels of individualised products require producers to accelerate technological innovations (Vielmetter and Sell 2014, Retief 2016). At the same time, shortened product life cycles force manufacturing companies to increase their production flexibility at lower response times in order to satisfy the specific customer requirements (Hasan and Shankar 2007, Angkiriwang, Puja-wan and Sandosa 2014). In addition to cost, quality and service level aspects,

customers increasingly integrate aspects which impact social and ecologic developments such as environmental protection and resource conservation on product and company level in their purchase decision-making (Kartnig, Grösel and Zrnic 2012), so that industrial producers are forced to identify with sound environmental practices. Consequently, business units have to face this paradox and challenge between increased product and service customisation versus the demand for low product cost at sound production practices (Retief 2016).

In this respect, business strategies such as Corporate Social Responsibility (CSR), Sustainable Production or Sustainable Supply Chain Management (sSCM) have experienced a surge in attention and stake in research and practice (Teuteberg and Wittstruck 2010:1, Bhardwaj 2016). In order to increase ecologic aspects in manufacturing, the concepts of lean and green manufacturing and thinking are driving approaches to foster the avoidance of waste and losses in combination with increased equipment efficiency and availability (Melton 2005:4, Duflou et al. 2012). As a result of the previous decade's development of energy prices, as well as decreasing natural resources, and through endorsement of public and political interests, producing companies require technical solutions for more ecologic and resource-saving equipment, procedures and processes (Bandow, Woetzel and Man 2013:1).

Attributing to the factors of decreasing resources and resource availability, as well as the demand for increased sustainability and system availability, the traditional objectives of industry such as cost, time, quality and operating efficiency have been supplemented by operating efficiency, system flexibility and adaptability as well as environmental issues, so that these dimensions majorly impact manufacturing operation and process design (Schenk, With and Mueller 2010, Mueller et al. 2013:1).

## **1.1 Research context**

The core function of any industrial company lies in its production which, by definition, is a combination of processes and methods in order to transform inputs into outputs (Panneerselvam 2006). The output of a manufacturing process consists of goods and/or services as well as any solid or liquid waste. This also in-

cludes emissions that are generated throughout the production process. The input to a manufacturing process consists of any raw materials, energy, labour, semi-finished products or components as well as any information and knowledge. The objective of modern manufacturing is the production of a high number of products with maximum efficiency at the lowest possible cost. High levels of standardisation and efficiency are achieved in line manufacturing which is characterised by high sensitivity to process interruptions and production downtimes, meaning that high service rates and system availability of all auxiliary and supply processes are required (Boysen, Fliedner and Scholl 2007).

Within manufacturing the transportation and handling of goods, components and materials are inevitable energy and time consuming parts of the production process. The auxiliary transport function is necessary to supply required items to the manufacturing process or to discharge finished products from assembly lines (Mueller et al. 2013). In the European Union transportation of goods including supply, intralogistics and distribution generates about 28% of the total CO<sub>2</sub>-emissions and consumes around 37.5% of the total European energy production (International Energy Agency 2014:37), whereas the fraction of energy related cost to total transportation cost is about 7% only (Fekete et al. 2014: 223). Of that, only 4% of the total energy as well as of the CO<sub>2</sub> emissions is related to pure production related materials handling (Sullivan, Burnham and Wang 2010) and by this contributes about 1,053.57 Mt of CO<sub>2</sub> emissions (International Energy Agency 2014).

Resource consumption and the emission of pollutants are often referred to as crucial factors in an attempt to evaluate industrial manufacturers' social and environmental responsibility. Resource consumption refers to the usage of raw materials for production equipment, manufactured products and inserted energy being necessary to operate the production processes. In reference to global emissions of pollutants, industrial manufacturing is one of the biggest producers of CO<sub>2</sub>-emissions with more than 22% of the global emissions while its energy consumption accounts for more than 28% of the global energy production (International Energy Agency 2014).

Several approaches in logistics and material handling focus on the reduction of CO<sub>2</sub>-emissions (Faulkner and Badurdeen 2014, Sparks 2014), material and energy consumption (Frade et al. 2011, Nie and Ghamami 2013, Jin 2016), as well as the improvement of overall system and process efficiency (Hess et al. 2012, Mueller, Krones and Hopf 2013, Giménez-Gaydou et al 2016), whereas growth rates of society and economy balance these developments and keep the levels of emission and consumption high. In the 2011 white paper, the European Commission sought to decrease transportation related carbon dioxide emissions by 60% by 2050 and also declared to ‘break the transport system’s dependency on oil without sacrificing its efficiency’ (European Commission 2011:5). In order to follow this guideline and to effectively counteract the impacts from production and transportation to resource consumption and pollutant emissions, technologies need to be adapted to manufacturing process requirements while increasing overall efficiency and system availability.

Driven by the cost of energy, increasing environmental consciousness, as well as developments of battery technologies, battery electric vehicles (BEV) are being publicly recognised as ecologic and economic alternatives to internal combustion engine vehicles. Electric vehicles are used in public transportation as buses and cars which are classified as road electric vehicles (rEV), while material handling related electric vehicles such as forklift trucks or order pickers refer to non-road electric vehicles (nrEV). Other technological alternatives such as fuel cell vehicles (FCV), plug-in hybrid electric vehicles (PHEV) or extended range electric vehicles (EREV) in public and industrial application lack technological maturity and application. Fully electric vehicles are characterised by high energy efficiency, no emission of tailpipe pollutants and bear the potential to be combined with renewable sources of energy in order to further increase their positive impact to system ecology (Office for Low Emission Vehicles 2013). In accordance with the introduction of new technical regulations for dangerous goods in 2008, the European Union achieved a major change from combustion engine vehicles to electric and battery electric industrial trucks and floor conveyors in intra warehouse material handling systems (European Commission 2011). This branch is thus characterised by increased experience in matters of electric vehicle integration.

A material handling system is a combination of several repeatedly occurring handling processes with the major function of changing the geographic location of goods through processing and transportation by using conveying machines, personnel and auxiliary equipment such as electric vehicle supply equipment (EVSE). A process is defined as a sequence of (process) functions, whereas a function is a task that equipment and/or personnel has to fulfil in order to enable the progress within the supply chain. Transportation functions along the assembly line mostly refer to automated processing on conveyor belts or automated guided vehicles. Supply of components to assembly lines is based on man-guided forwarding, as it requires higher flexibility and adaptability in accordance with alternating demand situations. The handling equipment requires energy to process the desired functions of a supply chain (Herrmann and Thiede 2009:4), so that energy provision, storage and consumption constitute crucial factors for system stability, availability and efficiency.

Research in reference to road-driven BEV underlines the importance in developing a dedicated energy supply infrastructure in order to allow the widespread realisation, implementation and usage of electric vehicles. Therefore research considers the development of an energy supply infrastructure based on different location-allocation models with the aim to efficiently supply BEV with the required amount of energy being necessary to satisfy the range requirements. According to Jin (2016), Giménez-Gaydou et al. (2016), Berman, Drezner and Krass (2010), Frade et al. (2011) and others, these investigations lack comprehensive analyses in order to determine charging station allocations, meaning that more accurate and application specific models are required. These have to integrate all system inherent impact factors such as process structures, charging coverage and adoption potentials into an innovative type of location-allocation model.

Operating times of nrEV in manufacturing generally exceed rEV driving times, whilst multiple process interruptions, break and idle times occur due to manufacturing process structures (Cromie 2011; Mueller, Krones and Hopf 2013). In nrEV environments and independent from process routing, scientific investigations assume that energy is available upon demand. As a consequence, energy supply simulations and optimisations need to change this focus to a more realistic perspective and to integrate process factors into more comprehensive investigations

(Herrmann and Thiede 2009:4, Shahraki et al. 2015:166, Jing et al. 2016:2), so that operating patterns in production related material handling might enable additional energy input by using inter-process break times for occasional recharging. The importance of a specific methodology and framework was also highlighted in the field of charging station implementation and allocation by the International Energy Agency report on hybrid and electric vehicles (International Energy Agency 2015: 81-88).

## **1.2 Research aim**

Research in the field of energy efficiency and material handling technology improvement in production related material handling has identified one of the major barriers in order to increase overall system efficiency as the lack of energy, process and technology based methodologies and frameworks that combine all aspects and components of material handling, such as material handling equipment, processes and electric vehicle supply equipment (Mueller et al. 2013). Research on models for charging station allocation in the BEV environment has noted the most suitable application to be a maximal (gradual) covering model so as to meet the requirements of BEV recharging (Frade et al. 2011; Giménez-Gaydou et al. 2016, Jin 2016) which corresponds to the pursued approach for optimised charging station allocation for occasional recharging.

The overarching aim of the pursued research project is to examine the impact and potential of contactless occasional recharging of nrEV in line manufacturing with a view to address the demand of business strategies such as Environmental Responsibility and Sustainable Production. Therefore the research aims consist of the

- (1) Identification and investigation of charging system integration relevant manufacturing process and energy related characteristics and performance indicators of material handling functions;
- (2) Provision of a comprehensive understanding about location-allocation models in related fields of charging station positioning through a survey of relevant literature, models and frameworks.

### 1.3 Thesis structure

The structure of the presented thesis is subdivided into a total of nine chapters that arise from a total of six subject areas (see Figure 1-1). The first chapter is an introduction to the field of the pursued research and presents the research project's aims; the second chapter executes the comprehensive literature review, including comprehensive information on research environment's technical components such as electric vehicles and electric vehicle supply equipment as well as the role of energy in material handling. In addition to this, the second chapter explains the fundamentals of location-allocation modelling, reviews and analyses existing models in reference to electric charging station allocation, identifies the research gap in this field and derives important information to the development of a dedicated model for occasional electric vehicle recharging. The third chapter reviews existing research methodologies and explains the research project's applied framework which is operated within the chapters four to six. As an integral component of the research project and being part of the setup phase, the process and energy data collection is explained and operated within the fourth chapter in order to define the fundamental structure for the development of a dedicated simulation tool, further referred to as OCSLM and explained in chapter five. Chapter six demonstrates the application of the simulation tool OCSLM to a total of seven investigations. Generated case study results are critically discussed within chapter seven in order to prepare the deduction of conclusions in reference to the impact analysis on occasional recharging to overall system efficiency and sustainability. Final conclusions are derived within chapter eight as the basis for recommendations on future research of chapter nine.

INTRODUCTION PHASE	1	Introduction	
PREPARATION PHASE	2	Literature Review	3 Research Methodology
SETUP PHASE	4	Data Collection	5 Analysis Design
APPLICATION/PROCESSING PHASE	6	Case Study Application	
DISCUSSION PHASE	7	Critical Discussion	
REVIEW PHASE	8	Conclusion	9 Future Research

Figure 1-1: Thesis structure

Source: Author



## 1.4 Chapter summary

Electric vehicles are widely used in transportation and, by reference, in material handling of manufacturing. In this regard, this branch has a high level of experience in matters of usage and application of this technology whereas in current practice driving distance and range limitations of EV result in over-dimensioning of battery capacities in order to avoid system downtimes and process interruptions (Herrmann and Thiede 2009:4, Mueller 2016). In reference to sustainable production strategies, companies demonstrate an increased willingness to integrate ecologic aspects in production planning and operations. Contactless occasional recharging in production is seen as a possibility to decrease non-used operation times, increase the amount of usable energy and by this improve manufacturing efficiency (Brecher and Arthur 2014), so that impacts and potentials of system integration based on most efficient charging station allocation is in the focus of the pursued research project.

# CHAPTER 2

## LITERATURE REVIEW

### 2.1 Introduction

The core function of the literature review is to provide the common understanding of all subject relevant aspects of a pursued research approach. It is responsible for the definition and explanation of research fundamentals including the research environment and all study-relevant components. Furthermore, the literature review incorporates a comprehensive investigation and systematic examination of existing research approaches, models, frameworks and information in respect to the selected research topic, so that it forms a substantial and important part of a research project (Dawidowics 2010). Knowledge of and reference to existing investigations and studies as a foundation for the chosen research approach demonstrate the integration of available knowledge and findings and show the connection point to the prevailing scientific landscape (Jesson, Matheson and Lacey 2011).

The research project by Brecher and Arthur (2014) on contactless power transfer systems for road electric buses identified five fields to be investigated in order to scientifically investigate and evaluate the technology implementation potential, so that these serve for the structure of the executed literature review:

- (1) Background
- (2) Technology
- (3) Demonstration
- (4) Standards and Regulations
- (5) Technology Readiness Level

In reference to the defined research aim of section 1.2, the executed research project focuses on investigating the fields (1) to (3), as technical standards and regulations on safety, health and environment (4) as well as technological design and maturity (5) are not integral parts of the research aim. In consonance with

this structure, the executions of the literature review focus on the identification, explanation and investigation of the three core aspects, such as

- (1) research environment
- (2) technological principles
- (3) system performance demonstration.

Hereinafter, the concept of sustainability in manufacturing will be explained as general framework and starting point of the pursued research approach. This introduction guides to the previously described research environment of production related component and material supply in line assembly manufacturing. High efficiencies and its requirements for stability and consistency in operations show the affiliation of line assembly to advanced processes and technologies, so that the potential of occasional recharging is investigated in this field and leaves space for future research in related applications that include material handling functions. The further explanations provide a comprehensive understanding of the research environment including material handling systems and processes. The technical components, i.e. technical aspects with relevance to the pursued analysis are explained in reference to aspect (2). The combination of relevant manufacturing, process and energy related performance indicators of material handling functions are explicated and investigated as a summarising step in order to form the basic framework for the review of location-allocation models destined for the impact analysis and potential evaluation.

As highlighted by Brecher and Arthur (2014: 41-42), further research has to execute performance analyses to foster the understanding of CPT operations, cost-benefits and performance trade-offs, so that the economic attractiveness and lifecycle benefits can thoroughly be investigated. Therefore and following to the environment and technology investigations, the second part of chapter two deals with an extensive literature review on existing location-allocation models for charging station allocation which constitute the basis for the evaluation of occasional charging system performance.

## 2.2 Lean and Green approaches in manufacturing

According to the definition of the U.S. Department of Commerce (2010), sustainable manufacturing can be described 'as the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound'. In addition to this, the Lowell Centre for Sustainable Production (2012) enlarges the sustainable perspective by the manufacturing system, i.e. the process components which are required to execute production processes and by this all auxiliary functions, so that 'sustainable production is the creation of goods and services using processes and systems that are non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for workers, communities, and consumers, and socially and creatively rewarding for all working people'. This definition draws attention to the importance of combining knowledge on process structures and characteristics with information on manufacturing systems in order to increase sustainable improvement and developments. Sustainable development by its own definition is 'a development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development 1987) and is built on its three pillars being economic, environmental and social sustainability (Elkington 1998). In order to increase the economic aspect of sustainable development, an increasing number of business entities refers to the application of lean principles to foster productivity and efficiency, to reduce costs, wastes and idle times. The primary function of Lean Management (LM) is to achieve the minimal appearance of waste and to achieve the optimal allocation of production resources with the target to create maximal value to the final consumer (Bortolini et al. 2016). Within Lean Management, the original seven types of waste such as transportation, unnecessary inventory, unnecessary motion, waiting queues, over processing, overproduction and defects have been enhanced by lost people skills being the 8<sup>th</sup> form of waste (Duees, Tan and Lim 2012, Verrier et al. 2013).

Inspired by the Lean approach, Green Management (GM) takes this development one step further by integrating environmental thinking into production and supply chain management being based on a comprehensive investigation of all product

life cycle phases including design, production and distribution as well as product use and disposal phases (Walker, Di Sisto and McBain 2008). Green Management differentiates among seven main types of waste of external nature being excessive use of water, excessive use of energy, excessive use of resources, pollution, rubbish, greenhouse gas effects and eutrophication (Duees, Tan and Lim 2012, Verrier et al. 2013).

While LM and GM share the overall target to minimise and eliminate waste, the properties of waste being tackled is different. Within Lean approaches waste is defined from the perspective of the end consumers as all non-value adding activities and functions in the product development and manufacturing process. GM defines waste to be of physical nature and focuses on environmental externalities with the target to minimise the negative impact to the environment. By this definition, waste presents an excessive and unnecessary use of resources as well as all contaminating releases to water, soil or air (Johansson and Sundin 2014).

Especially in the field of transportation there are conflicting target definitions between Lean and Green Management such as the target to achieve frequent replenishment and short lead-times versus the reduction of greenhouse gas emissions in reference to transport distances (Pampanelli, Found and Bernardes 2013, Duees et al. 2013, Bortolini et al. 2016). In contrast to this, several studies highlight the potential of combined, trade-off solutions of Lean and Green methods in order to contribute to both increased efficiency and ecology (Venkat and Wakeland 2006, Duues et al. 2013, Jabbour et al. 2013), where 'lean practices can lead to environmental benefits [and] inversely environmental practices often lead to improved lean practices' (Kleindorfer, Singhal and van Wassenhove 2005). In a first approach to structure and explain the dependencies between Lean and Green, Table 2-1 illustrates the impact from waste according to the Lean definition to the associated, ecologic output.

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Table 2-1: Lean waste and their associated green impacts  
Adapted from EPA 2007

The further investigation of the causal links between Lean and Green wastes, i.e. their dependencies, of Figure 2-1 highlights the complexity and the multiple, reciprocal impacts of these factors. The relations highlighted in red present the Green wastes that are likely to be connected to the liaised Lean waste, while the blue links present potential risks in between of these factors. As visible in Figure 2-1, transportation causally impacts excessive resource usage, excessive power usage as well as direct emissions to the air, soil and water, what highlights the importance to address these factors within correlating investigations.

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Figure 2-1: Causal links between Lean and Green wastes  
Adapted from Verrier, Rose and Caillaud ((2016:153)

As pointed out by several research approaches, most research in the field of combined Lean and Green Management evaluate cost as the first and greenhouse gas emissions as second key performance indicator (KPI) to be considered (Ahuja 2012, Azevedo et al. 2012, Dhingra, Kress and Upreti 2014, Martinez-Jurado and Moyano-Fuentes 2014, Bortolini et al. 2016), so that these indicators can serve as available comparison standards. In line with this, Bortolini et al. (2016:879) highlight the lack of numerical optimisation approaches as a gap within the existing field of research and therefore recommend to operate a quantitative optimal model based on cost and emission investigations.

A further differentiation by the Lowell Center for Sustainable Production categorises sustainable production into six, self-contained fields being characterised by mutual interactions. These are (1) energy and material use, (2) natural environment, (3) social justice and community development, (4) economic performance, (5) workers and (6) products (Veleva and Ellenbecker 2001:520). According to field (1), energy and material usage are closely interrelated, with the result that research field associated investigations are subject to combined investigations including the development of a dedicated and correlating framework. The fields (1), (2) and (4) correlate the fields as previously discussed, enlarge the technical perspective by sustainability and economic factors and, in doing so, underscore the importance of a comprehensive analysis.

An important aspect for the realisation and joint implementation of Lean and Green tools and methodologies lies in the analytical identification and quantification of improvement potentials that enable cost reductions, material and resource input, energy consumption and pollutant emissions (Aguado, Alvarez and Domingo 2013). The approach of eco-efficiency is closely related to sustainable production, as it constitutes a central milestone in its achievement (van Berkel 2006). In reference to sustainability, a further distinction into (eco-) efficiency and (eco-) effectiveness according to existing literature defines efficiency as an input/output oriented ratio of economy. Effectiveness expresses the degree of the achievement of specific objectives which, in reference to industrial production, is often referred to as financial cost (Scholz 1992:533). Pertaining to environmental sustainability, Dyllick and Hockerts (2002) define effectiveness as the main goal,

while efficiency is a possible objective. The identification and assignment of the pursued research approach is facilitated by the differentiation by Naef (1998:51):

**Efficiency** (doing the things right)

(1) How can the same output be achieved with less input? (2) How can more output in terms of quantity or quality be achieved with the same input?

**Effectiveness** (doing the right things)

(1) Are the endeavoured functions achieved by the actions operated, and how can the sequence of functions be designed more effectively? (2) Which functions make a high contribution to achieving the goals and are therefore important to expand and which functions make no or only little contribution?

From the executions on sustainability in manufacturing it can be deduced that in addition to pure cost-benefit examinations, analyses on system implementation performance have to integrate and investigate lean and green aspects in order to address the increasing demand for economic and ecologic sustainability, so that this research project investigates cost, resource consumption and CO<sub>2</sub> emission aspects.

### 2.3 Assembly line production

Assembly line manufacturing is a widely applied, flow-oriented production approach for the fabrication of high quantity standardised commodities in a cost efficient mass-production characterised by high specialisation of labour and the usage of learning curve effects (Shtub and Dar-El 1989). Driven by customer demand patterns and technical improvement, assembly line manufacturing has also gained importance in the production of low volume, customised products, meaning that production processes are subject to alternating quality of assembly materials and components which necessitates increased flexibility and adaptability of all related processes (Scholl and Becker 2004, Ericsson et al. 2010:49).

Within line assembly, production units perform operations successively in a serial manner being moved along the assembly line by an automated transportation system such as conveyor belts, automated guided vehicles or similar (Boysen, Fliedner and Scholl 2007). An assembly line consists of  $k = 1, \dots, m$  stations with each station progressively adding parts to the produced item by keeping a defined



sequence and balanced cycle times for the station function execution. The supply of these components can be operated by direct supply to the assembly line or by the integration of semi-finished components from other manufacturing processes. The complexity of all relevant production and feed-in processes necessitates an exact coordination and balancing in order to achieve a high level of efficiency within the manufacturing process (He and Kusiak 1998).

Profit maximisation based objectives in assembly line manufacturing focus on the reduction of any disruptive factors within production design and execution in order to decrease the fraction of time efforts and cost. As illustrated in Table 2-2 high levels of standardisation at a high ratio of process and system availability are key indicators for its achievement, whereas process characteristics, such as interruptions and downtimes have a high level of impact to the production efficiency (Chow 1990, Thomopoulos 2014).

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Table 2-2: Objectives and Characteristics of assembly line manufacturing  
Adapted from Chow (1990) and Thomopoulos (2014)

As highlighted by the executions on assembly line manufacturing, the integration of a charging infrastructure for occasional recharging needs to enable interruption free operations within existing process sequences in order to upkeep the production process efficiency (Brecher and Arthur 2014).

### **2.3.1 Material handling in assembly line environment**

Besides of the assembly function of line manufacturing, the supply of products to the assembly line, i.e. material handling, is one of the key functions to be executed in this work environment (Mueller, Krones and Hopf 2013). A number of alternative approaches, for example by Scholl (1999), Thomopoulos (2014), Kim, Kim and Kim (1996) or Ponnambalam, Aravindan and Mogileeswar Naidu (1998) illustrate and structure the interaction and combination of material handling resources and processes. While each of these models depicts a different approach

to the determination of line performance, the model by Chow (1990) captures the basic elements of line parameter functions.

In order to analyse a manufacturing assembly line in a structured way Chow (1990:7) subdivides line production into five elements such as (1) line flow and configuration, (2) line operation, (3) material logistics, (4) product yield and quality and, (5) information management.

In line with the evaluation by Chow (1990:6), the study by Boysen et al. (2015:113) highlights the negligence of scientific investigations surrounding material supply processes and structures in assembly line production as being a non-value-adding function. Material supply provides spare parts, components, semi-finished products etc. for assembly line work stations, which are usually provided in containers, shelves or boxes along the line (Boysen, Fliedner and Scholl 2007). Delays in material provision or supply of damaged products result in degraded line performance and increased production cost (Chow, W. 1990:6). The correlations of line parameters with impact to assembly line performance are shown in Figure 2-2. Material handling in assembly line environment has direct impact to line performance, but also impacts other functions of the assembly system such as interfailure and waiting times, scheduled and unscheduled downtimes and by this also indirectly influences performance numbers. A central aspect of line manufacturing is system availability, which is the proportion of time that a workstation and/or equipment can be used for production. Impacting time aspects consist of dead times, for example for system repair that has no potential for productive usage, as well as waiting times, downtimes, break and idle times that are not available for the central production process, but can be used for other auxiliary functions such as maintenance.

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Figure 2-2: Line performance as a function of line parameters  
Source: Chow (1990:11)

Investigating the ratio of process availability in reference to usable and unusable time properties, Chow (1990) highlights the employment of a methodology which integrates application measurements into a time and motion study. This combinatorial study has to integrate process related time fractions with process related movements of handling equipment including routing, actual position, function allocation and driving distances (Boysen, Fliedner and Scholl 2007:687). The execution of material handling in warehouse and production process environments is based on the insertion of electric energy, so that processes, functions and components need to be evaluated and examined based on their process energy consumption in order to analyse the impact to the system energy balance (Mueller, Krones and Hopf 2013). Therefore, energy consumption and expenditures form

the basis for all following analyses in order to address the cost and lean objective of assembly line production.

### **2.3.2 Material handling processes**

The definition of a 'process' in both material handling and manufacturing covers the material flow from a defined starting point to a defined destination point. However, in contrast to manufacturing, material handling does not include a change of the physical properties of the forwarded goods (Bandow, Woetzel and Man 2013). Material supply processes in production are based on picking, forwarding and delivery of supply materials. Order picking is defined as the process of clustering, re-arranging and forwarding of orders from pick up locations and its onward carriage to the place of demand (De Koster, Le-Duc and Roodbergen 2006:5). In addition to automated feeder lines, most material supply processes of assembly lines run on on-demand systems in order to provide systems that are flexible and adaptable to changing production patterns (Elgowainy, Gaines and Wang 2009, Jabali et al. 2014).

Human-employing order picking systems, that are the subject of the pursued research project, can be organised into three sub-categories such as Picker-to-parts, Parts-to-picker and Put systems. The picker is defined as a human being who operates process related tasks without or with the support of machines, such as forklift trucks or other handling devices under human command (Yu 2008).

The most common and flexible alternative in line assembly manufacturing material supply operates Picker-to-parts systems and is based on the movement of the picker to the fixed location of the shipment in order to pick and forward it to its place of destination (Mueller 2016). In a Parts-to-picker system an automated pre-process delivers the goods via an automated application such as a carousel or automated storage and retrieval systems (AS/RS) to the point of further forwarding or use. Put systems combine Picker-to-parts and Parts-to-picker approaches and therefore refer to semi-automated approaches (Yu 2008:6-7).

Figure 2-3 shows the simplified material handling process sequence in a Picker-to-part system which consists of the tasks such as approaching, pick up, transportation and delivery.

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Figure 2-3: Illustration material handling process

Based on Mueller (2016)

Basic functions of material handling equipment in reference to process operations are (1) approaching – unloaded driving, (2) pick up – free lift of cargo, (3) forwarding – loaded driving and, (4) delivery – unloading (Sople 2007:2). In some applications, stacking and unstacking are required functions that are part of (1) and/or (4). As illustrated in Figure 2-3, several break times can occur whilst operating material handling processes which differ in duration, frequency and location of occurrence.

The execution of material handling functions is operated on material handling system components upon the insertion of energy. Relevant material handling components and its influence to process energy consumption will be explained subsequently. This forms the basic understanding for the research framework for occasional recharging.

### **2.3.3 Material handling components**

Components for material handling in applications that are based on the usage of battery electric vehicles generally consist of three major elements such as (1) the handling equipment, (2) the battery and, (3) the electric vehicle supply equipment (EVSE). The following explanations introduce the reader to the major technical components of material handling and define the basic data and assumptions being necessary for the integration of technological relevant information to the application of a location-allocation framework.

#### **2.3.3.1 Handling equipment**

Essential components of material handling are considered to be lifting and handling equipment such as cranes, forklift trucks, order pickers etc. (Zrnic and Rajkovic 2011:3). In order to achieve the required degree of flexibility and adaptability

in production related material supply, handling equipment has to move between a large variety of points on variable paths. As per Table 2-3 industrial trucks as representative of floor conveying vehicles correspond to the demand for unrestricted area satisfaction, which offer variable process routing. Stacking and lifting can be realised by forklift trucks, whereas order pickers refer to planar movement of goods and materials only.

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Table 2-3: Transport equipment characteristics

Source: Kay (2012: 9)

Operator employing conveying processes lead to the concentration on forklift trucks (also named industrial trucks or lift trucks) which are integrated in most of the intralogistics processes due to their high technical and economic feasibility which combine lifting and planar movement and by this increase the range of use (Kay 2012:48). Typically, maximal lifting capacities of indoor trucks range from 1.3 tons to 2.6 tons (Elgowainy, Gaines and Wang 2009:3558). The advantages of lift trucks are based on their high flexibility to operate on different surfaces, the variety of available load capacities and the facilitation to work in five different degrees of freedom (Kay 2012:49):

- Horizontal translation (drive wheels)
- Horizontal rotation (turning wheels)
- Vertical lift (forks along mast)
- Mast tilt (forward tilt for un-/loading and backward tilt for travel)
- Fork translation (adaption to different size loads)

An important parameter of material handling equipment with impact to the energy balance of a material supply system is equipment energy consumption. Energy consumption is related to the truck acceleration, speed and payload in reference to process characteristics (Kleine-Moellhoff et al. 2012: 9) and needs to be powered from a portable energy source, i.e. a battery.

### 2.3.3.2 Battery

A battery is an electrochemical energy storage device and constitutes a central component of non-automated material handling equipment with average battery weights that account for up to 30% of the total vehicle mass (Mueller 2016). The most important function of the battery is to store and provide electric energy for the execution of handling functions such as driving and lifting of goods. As energy supply is an essential function for process operations, batteries are central elements for all system improvement and optimisation efforts. In addition to their core function, batteries can be used as counterweights in counterweight truck applications (Elgowainy, Gaines, and Wang 2009:3558).

In order to evaluate the applicability of batteries to electric vehicles, the United States Advanced Battery Consortium identified the categories of energy density, life-time and cost. These were added to by Kleine-Moellhoff et al. (2012:8) by the factors of efficient usage of resources and energy in order to address the demand for increased sustainability and eco-efficiency.

Cost of battery refers to the financial efforts to be taken in order to equip electric vehicles with an energy supply system being able to satisfy the process energy demand. In reference to EV, cost is a function of energy density of the battery technology, which itself is a dimension of driving range and energy demand. Cost minimisations in this respect refer to the adaption of battery capacity, i.e. the maximum vehicle range, to a minimum as a compromise of ensured system availability and the demand for sustainability and resource conservation.

The Depth of Discharge (DoD) refers to the fraction of energy that is stored in a battery and that can be retrieved to power the electric vehicle. The DoD is a measure for the resource and energy usage of a storage device by giving an input/output ratio in reference to the battery technology.

Life-time of batteries is based on the execution of full cycle equivalents and therefore needs to consider charging and discharging patterns of processes. In reference to occasional recharging, process patterns show multiple fragmentary discharging and charging actions with the target to increase Usable Battery Energy (UBE) during process operations, but as side effect increase battery encroach-

ment. Figure 2-4 illustrates the development of UBE in reference to interim recharging and by this shows the requirement to a battery system to stand multi-cycling within one working shift.

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Figure 2-4: Usable battery energy content with occasional recharging  
Adapted from Renquist, Dickman and Bradley (2012:4)

In 2016, most battery powered industrial trucks are powered on lead acid batteries, whereas its general application is based on the relatively cheap price and high technological maturity (Mueller 2016, Elgowainy, Gaines and Wang 2009). In contrast to this, most investigations evaluate lithium-ion technologies as leading technology for future applications (Kleine-Moellhoff et al. 2012). Table 2-4 compares relevant battery performance parameters of lead-acid and lithium-ion batteries with impact to their applicability for occasional recharging.

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Table 2-4: Battery performance parameters lead-acid vs. lithium ion  
Source: (left) Kleine-Moellhoff et al. (2012) and (right) Mueller (2016)

In addition to the above factors, fragmental cyclation of lead-acid batteries, being the result of short duration charging within numerous individual idle times, leads to a high level of degradation and therefore battery damage. Optimal operation



of lead-acid batteries is based on full-range battery charging from 0% to 100% or uncharging from 100% to 0% with no further limitation to the charging typology to be contact or non-contact charging. Due to the target to use multiple (short) time periods as well as due to the above mentioned factors, the usage of lead-acid batteries for occasional recharging can be neglected (Kleine-Moellhoff et al. 2012:21). Therefore, with a view to occasional charging this research focuses on the implementation of lithium ion batteries only, whereas a conventional lead-acid alternative serves as reference scale due to its wider industrial implementation.

### 2.3.3.3 Electric vehicle supply equipment (EVSE)

Conventional off-board chargers for electric vehicles such as lift trucks are based on unidirectional power flow, feeding the battery with energy from the grid, but do not inject energy into the grid (Yilmaz and Krein 2013). Bidirectional approaches in the field of mobile battery storage devices are used for load balancing, but are not a subject of this research.

Battery charging is differentiated into three charging categories according to the standards of the international Society of Automotive Engineers (2014) for electrical connectors for EV:

Level 1: Slow charging with a transmission performance up to 1.92kW

Level 2: Standard charging transmission performance is the predominant charging approach which ranges from 2.5kW to 19.2kW

Level 3: Fast charging refers to any charging performance which is higher than Level 2 up to 240kW

Conventional, conductive systems, which are predominantly used, are based on Level 2 charging (Mueller 2016). It employs the application of a physical metal-to-metal contact of a cable attached connector and charge inlet resulting in the necessity to plug in the cable for recharging (Budhia et al. 2011). Conductive chargers are typically located in designated, low-traffic areas which require approaching drives for recharging (Elgowainy, Gaines and Wang 2009).

In order to enable occasional recharging within non-value adding process times, charging systems need to be implemented in process range as fast connection solutions, so that process sequences and functions experience no extraordinary

disturbance. Inductive charging presents a model of fast connection charging which refers to a contactless energy transmission via air gap by using a magnetic field (Yilmaz and Krein 2012:2151, Brecher and Arthur 2014). Within electric vehicle material handling, the preparation for conventional plug-in charging before and after the charging process itself can be assumed to consume about 45 seconds, in contrast to about 1 second for contactless inductive coupling, and includes the operator getting off the vehicle, the exposure of the plug, unplugging of the battery from the vehicle, plugging the battery to the battery charger and the reverse actions after charging completion (Renquist, Dickman and Bradley 2012, Zheng et al. 2014). The development of a contact based charging system with lower connection times would enable occasional charging based on lower efficiency losses of contact energy transmission, while the results in reference to charging station positioning and system optimisation of OCSLM can be applied correspondingly. Caused by the additional time effort for contact charging preparations in comparison to contactless charging, existing contact charging solutions are not applicable for occasional charging related to idle times lower than 45 seconds.

The cordless alternative for re-charging bears several advantages, such as minimised handling efforts, fast connectivity and the opportunity for occasional charging (Lee and Lorenz 2011). Inductive systems are mostly implemented in research applications. Consequently the data that deals with this technology emerges predominantly from laboratory investigations. Existing battery chargers range from 12V / 24V / 36V / 48V to 96V, whereas 36V and 48V are most common by reaching 3.6kW / 7.2kW or 11 kW charging performance (Yilmaz and Krein 2013:2155-2160).

Contactless charging constitutes a more convenient, cordless way of recharging with no more need for plugging. An additional advantage of contactless power transfer (CPT) systems is the free embeddability throughout the warehouse in walls, floors, etc. (Imura, Uchida and Hori 2009:1) and its usage for intra process or interim occasional recharging (Brecher and Arthur 2014). A CPT system is characterised by a fixed primary conductor which is constantly energised and, through this, generates a magnetic field. The secondary winding is attached to the vehicle and, as soon as a consumer approaches, induces a current for direct

power supply to the electric engine or for charging it to the battery (Schulze and Wullner 2006:2). Figure 2-5 shows the layout of an inductive system, transferring the energy via an air gap from the primary transducer / coil to the secondary transducer / coil where the magnetic field induces an alternating electric current. After rectifying it to direct current it can be stored in the battery.

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Figure 2-5: Stationary inductive charging station  
Source: Yilmaz and Krein (2013:2160)

Transmission efficiency of inductive systems is majorly impacted by misalignment on x- and y-axis and air gap on z-axis, i.e. the space between primary and secondary coil due to integration of the primary coil in the floor and the vehicle's ground clearance. As Kaneko and Abe (2013:1) state, existing CPT systems that offer similar transmission performances as applicable for nrEV meet the requirements for occasional recharging such as high efficiency around 90% (conductive charging ~ 96%), large air gap and high tolerance to misalignment.

The previous descriptions highlighted technology based characteristics with impact to the performance evaluation of the system implementation, so that these represent the indicators to be considered within infrastructure allocation determination.

## **2.4 Performance indicators in EV material handling**

Lean manufacturing and sustainability approaches aim to run material handling processes by using the most energy efficient activities and technologies in order to avoid any waste such as excess inventory, down times, cost and/or unavailability of equipment (Seow and Rahimifard 2011:6; Sullivan, McDonald and Van Aken 2002:4). Supporting this target, energy management strives to further reduce waste and losses by holistically analysing process chains through monitoring, structuring and documenting energy requirements such as demand and supply, so that the importance of effective performance measurement grows

(Mueller, Krones and Hopf 2013:2). The named factors and aspirations majorly impact the design and operations of applied material handling functions.

The previous executions of chapter 2 explained subject related components with relevance to the development of the research framework. The executions emphasised performance indicators in reference to assembly line production, material handling as well as its processes and components to the point that these present the choice of factors to be considered for the determination of research target relevant performance indicators.

The explanations on assembly line production highlighted the importance of high production times which are based on the avoidance of process interruptions and down times. The reduction of disruptive factors leads to a high ratio of process and system availability. Material Handling focuses on the provision of constant system availability based on the avoidance of dead times, waiting times, down times, break and idle times. A further differentiation in usable and unusable fractions allows the re-evaluation and usage of unusable main process times to usable times for auxiliary functions, whereas the integration of time and motion studies as combination of equipment and process data may lead to increased overall efficiency. The consequence is the investigation of process sequences and functions based on energy requirements for its execution as per explanations of subsection 2.3.2 [p.19].

Mueller et al. (2013) as well as Mueller, Krones and Hopf (2013) identified performance indicators with impact to energy efficiency in production facilities such as 'minimal and maximal equipment performance', 'operations', 'operation and process times', 'connection power' and 'efficiency'. In line with the previous explanations and the model on line performance functions of Chow (1990), key performance indicators (KPI) in reference to the research environment and subject are deduced as illustrated in Figure 2-6.

MH equipment energy consumption refers to average acceleration, speed and forwarded payload in reference to its process functions. Battery based parameters are influenced by driving ranges, battery capacity as well as dis-/charging patterns in reference to transmission performance, transmission efficiency and usable idle times that are available as additional charging times.

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Figure 2-6: Performance indicators of material handling

Adapted from Chow (1990); Mueller et al. (2013) and Mueller, Krones and Hopf (2013)

Within the investigation on the impact of occasional recharging to the system energy balance and the evaluation of its potential regarding resource and material savings, i.e. the adaption of integrated battery capacity to process energy demand and additional energy input, it is sufficient to consider the performance indicators which follow subsequently to the 'Usable Battery Energy' (see Figure 2-6). Equipment availability needs no additional consideration as usable idle times are considered within process potentials for additional energy input and UBE targets to match existing energy demand. As economic standard, down times and dead times are integrated in the illustration in order to calculate the ratio of equipment availability, whereas it has no informative character to the pursued research approach. In real application UBE needs to contain excess energy for safety reasons in alternating processes, so that this needs to be considered within system optimisation calculations.

As per illustration of Figure 2-6 and the explanations of subsection 2.3.2 [p.19], process immanent idle times need to be differentiated more precisely in order to be evaluated for their applicability to occasional recharging. Idle times can be evaluated to be usable or unusable for occasional recharging (Mueller, Krones and Hopf 2013). The differentiation needs to be based on the positive contribution to the system energy balance being integrated as a corresponding function (Berman, Drezner and Krass 2010). Work related dead times, as well as downtimes are assumed to be necessary for maintenance or short in duration so that these cannot be used for any value adding (Thomopoulos 2014) or recharging activity.

From the above executions, several fundamental requirements to the evaluation of the applicability of a location-allocation model are deduced. In reference to the performance indicators as per Figure 2-6, these parameters need to be included in a comprehensive framework in order to address the quality characteristics of the investigated research environment (Mueller, Krones and Hopf 2013). The breakdown of the performance indicators of Figure 2-6 into function related value units is shown in Table 2-5. The deduced parameters serve as criteria for the qualification of the reviewed location-allocation models.

Energy Consumption Data	Process Data	Supply Data
Voltage driving (un-) loaded	Position (x / y)	Transmission performance
Current driving (un-) loaded	Operating / idle times	Transmission efficiency
Voltage lifting	(Un-) Loaded operations	
Current lifting	Speed	

Table 2-5: Fundamentals to location-allocation models

Source: Author

The following part of chapter two first introduces the fundamentals of location-allocation models and decentralised energy supply models which are essential for the differentiation and categorisation of different alternatives and models. Based on the gathered knowledge about the application areas, existing models in the area of charging station allocation are reviewed and evaluated towards the applicability within the defined area of research, based on the developed requirements of production related material supply. Section 2.6 compares the qualification criteria with the characteristics of existing allocation models in order to investigate the existence of a research gap in this field.

## 2.5 Decentralised energy supply modelling

The notion of occasional recharging in non-automated electric vehicle material handling aims to provide additional usable battery energy to the system without additional disturbance of processes, while using existing process sequences and process interruptions. In this way the research approach correlates to the operation of an integrated decentralised energy supply which targets to relocate battery charging from designated and separated areas to more efficient, process integrated spots. An important part in this field of research is related to the design

and implementation of a corresponding charging infrastructure to nrEV operations, i.e. the determination of most beneficial implementation of charging stations (Giménez-Gaydou et al. 2016).

The approach of Giménez-Gaydou et al. 2016 relies on a comprehensive analysis of process energy requirements, consumption and charging needs as well as the adoption potentials being realised in a specific type of location-allocation modelling. In reference to this, the demand for increased efficiency within charging station implementation is added to the previously identified qualification criteria for the application of location allocation models. Based on the results of the previous part of the literature review on requirements to the application of a designated location-allocation model, existing models have to be investigated based on characteristics that integrate all performance indicator aspects. These indicators, shown below, constitute the criteria for the evaluation of the applicability of existing models and frameworks:

- Focus on system efficiency optimisation
- Integration of process data
- Integration of reliable and accurate energy data based on technology specifications
- Integration of energy supply characteristics

The overall target of location planning is to identify the optimal location of one or more facilities, whereas the term 'optimal' is characterised by a high dependency on the quantification of input data. Church and ReVelle (1974) highlight the accuracy of a location problem solution reflecting the quality of data that has been used to process the analysis, meaning that target specific data with flexible but accurate resolution is an essential part of any scientific location model.

Optimised charging infrastructure allocation serves as a starting point for the pursued research in order to calculate and evaluate the technical potential for occasional recharging, so that an evaluation of the calculation principle based on the above defined aspects is set as qualification standard for the identification of relevant literature on charging station allocation. As the aim of this research ap-

proach is to investigate the impact of occasional recharging to the system's energy balance, eligible frameworks have to enable examinations on the impact to battery design, resource savings and sustainability.

Figure 2-7 shows available categories of location planning alternatives as well as its core specifications and evaluation against the defined criteria. As displayed, Economic Location Theory shows the lowest degree of requirement fulfilment as its major focus lies on the development of forecasts, especially on the supply side in factory allocation (Goetz, Deller and Harris 2009). The model allows a low level integration of process or energy data and is not designed for system optimisations. Layout Planning models are process oriented and focus on the design of new processes with the target to generate a lean manufacturing design (ReVelle and Eiselt 2005). Investigations on the retroactive implementation, i.e. the retroactive optimisation of charging station allocation is not featured, so that results of the pursued research project can be used within Layout Planning to support future manufacturing design, but shows low applicability within the current research phase.

While Location-Choice models are operated on a probabilistic choice of supply nodes, the previous part of the literature review highlighted the demand for a deterministic identification based on realistic process and energy values. In addition to this, Frade et al. (2011) as well as Giménez-Gaydou et al. (2016) explicitly highlight the suitability of Maximal Covering Models as Location-Allocation alternative to cope with the requirements of EV charging station allocation. Its focus lies on the optimisation of system efficiency based on the maximised usage of charging stations under fractional demand coverage (Giménez-Gaydou et al. 2016:4). MCL Models, in contrast to LSCM, focus on the maximisation of coverage with a pre-defined number of supply facilities. The result is a maximal fraction of demand being satisfied meaning that, in contrast to LSCM, a certain fraction remains unsatisfied. This factor is considered to be of high importance to the applicability of a charging station allocation as inefficient demand spots are excluded from charging station allocation (Frade et al. 2011).

A more detailed evaluation and consideration towards the research application of a MCLM among the available range of models as illustrated in Figure 2-7 including individual mathematical formulations can be found in Appendix A.



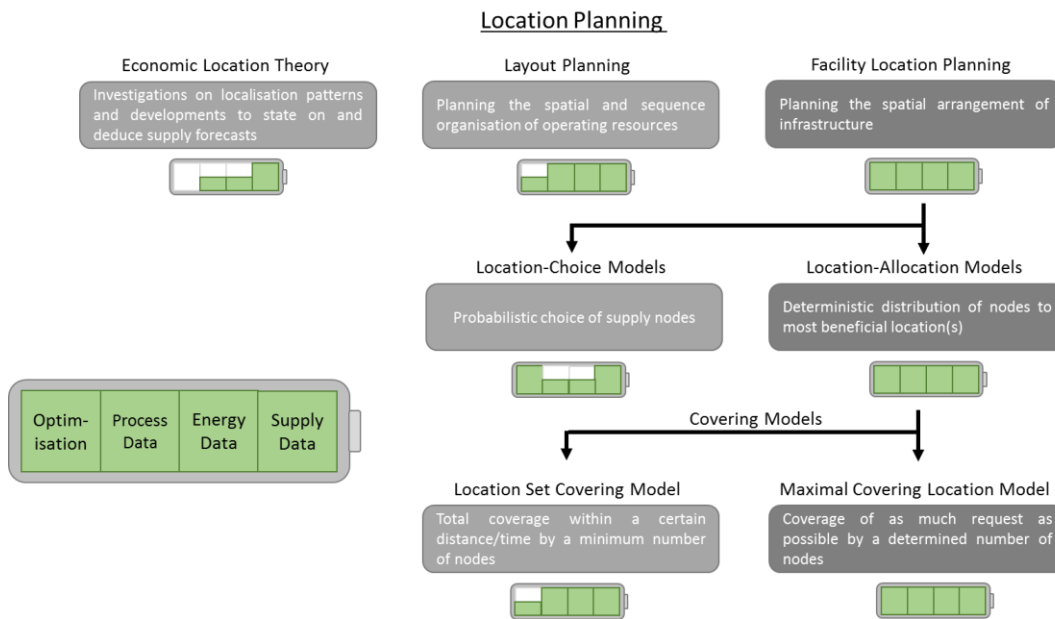


Figure 2-7: Qualification of Location Planning models

Source: Author

As a reference to MCL modelling, the basic mathematical definition is shown below. In order to address the optimisation requirement, i.e. the number of demand being subject to coverage ( $b_r$ ), basic MCLM according to Church and ReVelle (1974) integrates the binary variable  $z_r$  as decision variable to the maximisation term as per equation (1).  $z_r$  is set to equal the value of 1 if a demand spot  $r$  lies within a defined ‘covering distance’  $a$ ; 0 if not. In doing so, the described efficiency aspect within the cover distance definition in reference to charging times can be integrated.

The basic MCLM according to Church and ReVelle (1974) is formulated as:

$$\max \sum_{r \in R} b_r z_r \tag{1}$$

$$s.c. \quad z_r \leq \sum_{j \in X_r} y_j \quad \forall r \in R \tag{2}$$

$$\sum_{j \in J} y_j = s \quad \forall r \in R \tag{3}$$

$$y_j = (0,1) \quad \forall j \in J \tag{4}$$

$$z_r = (0,1) \quad \forall r \in R \tag{5}$$

In contrast to other models (see Appendix A), MCLM maximises the weighted number of demand spots that are located within the covering distance  $a$  (1). This perspective changes the focus from the minimisation of cost, such as time and/or

distance, and enables investigations on increased effectiveness and efficiency of resources. Equation (2) allows the coverage of a demand spot  $r$  only if one or more facilities are located within the range  $a$ . (3) limits the number of facilities  $J$  to the defined number. (4) and (5) define the variables to be of binary nature.

The displayed characteristics of MCLM are the basis for most existing models on electric charging station allocation (Giménez-Gaydou et al. 2016) which are displayed and analysed towards their applicability for occasional charging in the following.

## **2.6 Approaches to electricity supply infrastructure allocation**

The literature review on location models displays a large number of publications and scientific work in the field of charging station allocation for road electric vehicles using different specific strategies and methodologies in order to accomplish specific research targets, whereas 30 of these were investigated more thoroughly within the literature review due to their reference to the identified qualification criteria. Existing research in the field of charging station allocation exists in the field of EV and focuses on cost minimisation and optimisation for charging infrastructure integration (Nie and Ghamami 2013, Mak, Rong and Shen 2013, Chen, Kockelmann and Khan 2013), minimisation of additional trip time (Hess et al. 2012, Sweda and Klabjan 2011) and the reliable provision of driving range (Wang and Lin 2009, Li et al. 2010). A few frameworks make the attempt to develop an integrated and holistic approach to charging station allocation, whereas metrics and frameworks are majorly based on vague, estimated or approximated figures (Berman, Drezner and Krass 2010, Giménez-Gaydou et al. 2016, Jin 2016). The field of charging station allocation for non-road electric vehicles in industrial application has been largely neglected by scientific investigations, meaning that existing scientific literature and models on electric charging station allocation for rEV is considered as available reference.

The previous part of chapter 2 defined the research environment and identified important, critical factors for the qualification of existing frameworks to the specific application. This serves for the identification of a dedicated framework for charging station allocation in production related material handling in order to evaluate the energy potentials of occasional recharging to sustainable system design. The

following part investigates existing models and frameworks in the field of charging station allocation for rEV and by this assesses their applicability for occasional recharging in an industrial non-road electric vehicle environment.

Within the comprehensive literature review, a total of 30 models from the field of charging station allocation for electric vehicles with impact to the research approach have been identified and reviewed in reference to the defined performance indicators (Table 2-6). To narrow down the number of research approaches to be included as basis for the definition of a subject specific model and to increase the quality of the considered contents, existing models have been qualified according to their reference to the identified performance indicators as per section 2.5. The classification of existing research to the identified categories highlights the consideration of these aspects within these investigations, whereas research specific requirements are not (always) fully met. Due to the research project's focus on a process-based system integration in reference to process characteristics and process energy consumption, research that focuses on one or both of these parameters was of preference.

	Author(s)	allocation model	car type	efficiency improvement	process data	energy data	supply data
1	Berman, Krass and Menzenes (2007)	Median	rEV	x	x		
2	Berman et al. (2009)	Median	rEV	x	x		
3	Berman, Krass and Wang (2011)	MCLM	rEV	x	x		
4	Berman and Wang (2010)	Median	rEV		x	x	
5	<b>Berman, Drezner and Krass (2010)</b>	MCLM	rEV	x	x	x	
6	Chen, Kockelmann and Khan (2013)	Median	rEV		x		
7	Chen and Kockelmann (2014)	LSCM	rEV		x		
8	Chen,Wang and Kockelmann (2015)	LSCM	rEV		x		
9	Dashora et al. (2010)	Median	rEV		x		
10	<b>Frade et al. (2011)</b>	MCLM	rEV	x	x	x	x
11	<b>Giménez-Gaydou et al. (2016)</b>	MCLM	rEV	x	x	x	
12	Goh and Sim (2010)	LSCM	rEV		x		
13	Hanabusa and Horiguchi (2011)	Median	rEV		x		
14	He et al. (2013)	MCLM	PHEV		x		
15	Hess et al. (2012)	Median	rEV	x			x
16	Hodgson (1990)	Median	rEV	x	x		
17	Ip et al. (2010)	Median	rEV		x		
18	Jin (2016)	MCLM	rEv			x	x
19	Kuby and Lim (2005)	MCLM	AFV	x	x		
20	Kuby and Lim (2007)	MCLM	AFV	x	x		
21	Li et al. (2010)	MCLM	rEV		x		
22	Lim and Kuby (2010)	MCLM	AFV	x	x		
23	Mak, Rong and Shen (2013)	LSCM	rEV		x		

24	Nie and Ghamami (2013)	LSCM	rEV			x	x
25	Pan et al. (2010)	LSCM	PHEV		x		
26	Sweda and Klabjan (2011)	Median	rEV		x		
<b>27</b>	<b>Upchurch, Kuby and Lim (2009)</b>	MCLM	AFV	x	x	x	
28	Wang and Lin (2009)	LCSM	AFV			x	
29	Wang and Wang (2010)	MCLM	rEV	x			
<b>30</b>	<b>Xi et al. (2013)</b>	MCLM	rEV	x	x	x	x

Table 2-6: Electric charging station location-allocation models

Source: Author

In line with the Pareto qualification standard, the top 20% of ranked research approaches in reference to individual contents was to be identified. As eight of the reviewed 30 models present enhancements of previous models (compare Berman, Krass and Menzenes 2007 till Berman, Krass and Wang 2011 and Chen, Kockelmann and Khan (2013) to Chen, Wang and Kockelmann 2015 as well as Kuby and Lim 2005 till Lim and Kuby 2010), the top 20% result in a total of four models to be identified for further revision. Model qualification with regard to content highlights the models by Frade et al. (2011) and Xi et al. (2013) that address all four of the identified research performance criteria. Following the model qualification approach, amongst the total of identified models only the models by Upchurch, Kuby and Lim (2009), Berman, Drezner and Krass (2010) and Giménez-Gaydou et al. (2016) address three of the four defined performance components while being of similar focus (see also Table 2-6). A further differentiation among these models is evaluated to not positively contributing to improved model qualification, so that all five identified models (see Table 2-7: Related research) are considered for more detailed investigation and revision towards applicability to the pursued research approach. The remaining models according to Table 2-6 are not of further attention to the pursued research project due to the research specific model qualification, whereas their existence and contribution to individual aspects of charging station allocation shall be acknowledged at this point.

	Author(s)	allocation model	car type	efficiency improvement	process data	energy data	supply data
<b>5</b>	<b>Berman, Drezner and Krass (2010)</b>	MCLM	rEV	x	x	x	
<b>10</b>	<b>Frade et al. (2011)</b>	MCLM	rEV	x	x	x	x
<b>11</b>	<b>Giménez-Gaydou et al. (2016)</b>	MCLM	rEV	x	x	x	
<b>27</b>	<b>Upchurch, Kuby and Lim (2009)</b>	MCLM	AFV	x	x	x	
<b>30</b>	<b>Xi et al. (2013)</b>	MCLM	rEV	x	x	x	x

Table 2-7: Related research

Source: Author

As illustrated in Table 2-7 all models that are subject to more detailed investigations are based on Maximal Covering Location approaches, whereas the literature review of subject relevant research as per Table 2-6 included LSCM (with 24.1% of all reviewed models) and Median based approaches (34.5% of all reviewed models). The focus on MCL models goes in line with the initial evaluation of Frade et al. (2011) as well as Giménez-Gaydou et al. (2016) for rEV charging station allocation.

The basic applicability of existing MCLM for nrEV charging station allocation for occasional recharging is evaluated in the following passage by investigating and critiquing existing models in this field of research. The critiquing of the identified, relevant literature used a standardised critique worksheet and reviewed all integral research components such as Study Purpose, Research Design, Literature Review, Research Question/Hypothesis, Study Sample, Data Collection, Study Results and Study recommendations (see Boswell and Cannon 2011:293-300). In reference to the request of Coughlan, Cronin and Ryan (2007), the operation of research critique has to point out the research strengths, weaknesses and recommendations for further improvements, so that in a combined investigation the critique on location-allocation models illustrates the individual research context, research application, model theory, strengths, limitations and given recommendations for further research. The qualified models are explained in short and evaluated according to their fulfilment of the required performance criteria in the following subsections 2.6.1 to 2.6.5, so that implications and recommendations for further research can be deduced.

### **2.6.1 Model A – Flow Refuelling Location Model**

The Capacitated Flow Refuelling Location Model (CFRLM) proposed by Upchurch, Kuby and Lim in 2009 is an advancement of the FRLM model by Kuby and Lim (2005 and 2007). The initial model FRLM focuses on the location optimisation of a limited number of refuelling stations by trying to maximise the number of trips by a fleet of vehicles under the assumption of range limitation. FRLM is an uncapacitated approach, so that single facilities have the potential to completely refuel vehicles without station and vehicle limitations. In contrast, the advancement CFRLM takes facility and vehicle capacities into account and limits

the amount of flow for refuelling by individual facilities, meaning that the number of vehicles and the energy to be refuelled is limited.

The approach by Upchurch, Kuby and Lim focuses on the maximisation of vehicle miles travelled (VMT) instead of the maximisation of vehicle trips. The focus on VMT shows the changing reference to the required distance and by this energy consumption to be covered instead of the number of trips only.

CFRLM and FRLM optimise facility locations in reference to the flows between origin and destination. These flows are defined as 'captured' if a minimum of one facility is located on the path/route of a vehicle. In reference to the consideration of distances by CFRLM, multiple facilities can be used in order to refuel the investigated vehicles. This is an inevitable part for the investigation on both short and long distance ranges. The basic FRLM formulation according to Kuby and Lim (2005) is:

$$\max Z \sum_{q \in Q} f_q y_q \quad (6)$$

*s.c.*

$$\sum_{h \in H} b_{qh} v_h \geq y_q \quad \forall q \in Q \quad (7)$$

$$x_k \geq v_h \quad \forall h \in H; k | a_{hk} = 1 \quad (8)$$

$$\sum_{k \in K} x_k = p \quad (9)$$

$$x_k, v_h, y_q \in (0,1) \quad \forall k, h, q \quad (10)$$

$y_q$  is set to 1 if it lies on the O-D route and 0 if not.  $x_k$  is set to be 1 if a facility is located at  $k$  and 0 otherwise. A value of 1 for  $v_h$  indicates that all installed facilities are opened, 0 if not. The factor  $q$  represents a constant index of O-D pairs, i.e. the shortest bidirectional route from origin to destination, whereas  $Q$  is the set of all considered O-D pairs.  $f_q$  is the flow volume between the O-D pair  $q$ . In this discrete model,  $K$  is the sum of all possible facility locations to be installed with  $k$  as its index and  $p$  as the total number of facilities to be installed.  $H$  is the set of all potential facility combinations. Due to the restriction to no or minimal deviation from driven routes, the number of potential combination increases with the  $Q$  and

$K$  and by this raises complexity. The coefficient  $a_{hk}$  is set to 1 if the facility  $k$  is part of the combination  $h$  and 0 if not.  $b_{qh} = 1$  defines the capability of a facility combination  $h$  to refuel the O-D pair  $q$ , 0 if not.

The target function (6) maximises the captured flow volume and by this maximises the possible energy input with the restriction that refuelling must be allocated on the defined O-D routes. Side condition (8) integrates the capacity factor as refuel stations are not constantly available. This factor can be neglected for the pursued research approach as charging stations are available, except of technical outage. (7) expresses vehicle range in reference to maximum distance demand and vehicle range limitation.

The contribution of FRL models to efficiency improvement is based on the maximisation of charging energy to the investigated objects, so that other investigations build on this model such as Nie and Ghamami (2013:173). Increased usable energy contributes to increased travel distance and by this, availability of equipment. Refuelling stations are allocated on existing routes or in optimised allocations within range of minimised additional driving efforts, whereas there is no explicit range definition in FRLM. Liu and Sun (2014) criticise this definition of the covering distance as well as the discrete modelling approach to decrease charging station location efficiency.

Process data of FRLM and CFRLM is based on probabilistically forecasted origin-destination (O-D) pairs and the flow volumes between them. The target of both approaches is to minimise the paths between all O-D points and to determine the combination of facilities in order to provide constant availability and round trip range provision (Kuby and Lim 2005). Energy consumption in the explained approaches is not explicitly integrated but is expressed by referring to a maximum range of O-D round trips. Travel distances in reference to maximum range of vehicles present a first integration of energy consumption to location-allocation investigations whereas integrated numbers are based on range and distance estimations. By this, vehicle specific data is not integrated, so that energy consumption is evaluated to be rough and not in the focus of the pursued investigations. Furthermore, Xi, Sioshansi and Marano (2013) highlight the model's negligence of vehicle movement and arrival patterns as well as the reference to a fixed flow-capture capacity.

The integration of supply data is neglected in FRLM as supply facilities are uncapacitated and are not related to fuelling or fuelling time limitations. CFRLM integrates supply capacities but only in reference to average daily fuel availability, meaning that fuelling process characteristics are not included.

Within the analysis by DeSousa and Rossi (2014), the authors remark the model's missing reference to competition factors, so that it is characterised by decreased applicability for cost-benefit analyses.

The following Table 2-8 shows an excerpt of the critique worksheet and summarises the results of the critique on the CFRL model by Upchurch, Kuby and Lim. The last row of the table includes implications of the executed research and by this recommendations to further research as highlighted by the model researchers.

<b>Research Context</b> Purpose of the study	<ul style="list-style-type: none"> <li>- Location-allocation for alternative fuel stations</li> <li>- Advancement of an uncapacitated Flow refuelling location model</li> <li>- Focus on more realistic representation of range limitations</li> <li>- Range requirement satisfaction</li> </ul>
<b>Application</b>	<ul style="list-style-type: none"> <li>- Application to intercity network</li> <li>- Simplified case study</li> </ul>
<b>Theory</b> Framework	<ul style="list-style-type: none"> <li>- Capacitated Flow Refuelling Location Model</li> <li>- Maximisation of vehicle miles travelled</li> </ul>
<b>Strengths</b>	<ul style="list-style-type: none"> <li>- More realistic assumption on refuelling capacities</li> <li>- Reference to distances to be covered instead of vehicle trips</li> <li>- Rich study background</li> </ul>
<b>Limitations</b> Weaknesses	<ul style="list-style-type: none"> <li>- Reference to fixed study region</li> <li>- Usage of simplified O-D traffics (gravity model estimation)</li> <li>- Reference to estimated, forecasted values</li> </ul>
<b>Recommendations</b> and implications	<ul style="list-style-type: none"> <li>- Application of more realistic research environment</li> <li>- Usage of real O-D data</li> <li>- Usage of continuous model</li> <li>- More accurate quantity of range/fuel needed, i.e. energy consumption</li> </ul>

Table 2-8: Critique worksheet Upchurch, Kuby and Lim (2009)  
Source: Author



### 2.6.2 Model B – Gradual Cover Model

Berman, Drezner and Krass (2010) describe the gradual and cooperative cover model (GCM) based on MCLM. The research highlights the weakness of existing covering models of the time being by their reference to imprecise and unrealistic assumptions. These fundamentally unrealistic assumptions are divided into the below three categories (Berman, Drezner and Krass 2010:1676):

A1: All or nothing coverage

A1 defines any demand spot to be completely covered if it lies within the defined covering distance. A degradation of the demand value is not considered. Demand spots marginally out of covering range are not considered.

A2: Individual coverage

A demand spot is always covered by the closest supply facility. Especially in capacitated investigations, referring to next-closest facilities needs to be considered in order to maximise demand satisfaction.

A3: Fixed coverage radius

The coverage radius, i.e. the maximum (additional) travel distance or time, which determines a demand spot to be within or out of covering distance is determined exogenously as basic assumption and by this does not present a decision variable.

An aspect of the gradual covering model is to break assumption A1 by partially integrating demand spots at a certain distance from the supply spot in order to relax the precise differentiation of capture. In combination with A2, this implies that also more than one facility can be used in order to satisfy an individual demand spot. This goes in line with the specification of variable radius models that determine the covering range as endogenous function of cost in order to address the shortcomings of MCLP as per A3.

Berman, Drezner and Krass (2010:1679) suggest to include several increasing covering distances in consideration of decreased demand to be satisfied, meaning that for covering constant  $a_k$  with  $k = 1, \dots, c$  the coverage radii are defined as  $R_1 < R_2 < \dots < R_c$ . The impact of demand point  $i$  with a weighting factor  $w_i$  to facility allocation decreases with an increasing  $c$ . The benefit of coverage decreases with increasing distance, so that  $1 = a_1 > a_2 > \dots > a_c$ .

The general gradual cover model can be described as:

$$\max_{S \in X, |S|=p} \sum_{i \in N} w_i f_i(d_i(S)) \quad (11)$$

$S$  represents the set of available facilities with  $|S| \leq p$  and  $p$  being the number of facilities to be placed. The factor  $d_i$  is the distance between demand in  $i$  and the facility in  $j$ . The coverage function is  $f_i(d)$  with  $f_i(d) = 1$  for  $d \leq R$  and  $f_i(d) = 0$  for  $d > R$ .

The positive contribution to coverage maximisation of all covered demand spots to the set of installed facilities  $X$  is expressed by  $X_i = \{j \in X \mid d(i,j) < R_{\max}(i)\}$ . Replacing  $w_i f_i(d(i,j)) = b_{ij}$  with  $j \in X_i$  produces the target function (12). The binary variable  $y_{ij} = 1$  defines the available facility at  $j$  as being closest to  $i$ .  $x_j = 1$  defines this facility to be available and 0 if not, so that the GCM can be formulated as:

$$\max_{i \in N} \sum_{j \in X_i} b_{ij} y_{ij} \quad (12)$$

s.c.

$$\sum_{j \in X} x_j = p \quad (13)$$

$$x_j \geq y_{ij} \quad \forall i \in N; j \in X_i \quad (14)$$

$$\sum_{j \in X_i} y_{ij} \leq 1 \quad \forall i \in N \quad (15)$$

$$x_j \in (0,1) \quad \forall j \in X \quad \text{and} \quad y_{ij} \in (0,1) \quad \forall i \in N, j \in X_i \quad (16)$$

The contribution of GCM to increased efficiency in location-allocation modelling emerges due to the integration of partial volumes of demand in order to increase the degree of coverage, so that also the model by Giménez-Gaydou et al. (2016) integrates this aspect of this approach. By this, each infinitesimal positive consideration of demand, which in the pursued research approach is later defined as break time, increases the rechargeable energy potential.

GCM integrates processes by considering flows and travel routes, as well as distances. The decay function for coverage represents additional efforts in respect to time and distance by decreasing the fraction of demand being covered,

whereas Eiselt and Marianov (2015:227) as well as Dell’Olmo, Ricciardi and Sgalambro (2013:108) critique that the definition by Berman, Drezner and Krass only presents a piecewise decay function to integrate partial coverage. For the pursued investigations, this procedure bears the potential to integrate process data such as break times, as well as energy consumption data in order to balance recharge energy potentials and energy efforts for facility approaching, whereas Eiselt and Marianov (2015:227) highlight the model’s imprecise integration of energy supply characteristics. Blecker, Kersten and Ringle (2014:170-171) criticise the model’s stochastic radius definition as well as the demand coverage to be based on a shortest distance definition, so that charging station approaching decision might be inefficient in a real application. The model critique key findings as well as author’s research recommendations are illustrated in Table 2-9: Critique worksheets Berman, Drezner and Krass (2010)

Source: Author

<b>Research Context</b> Purpose of the study	<ul style="list-style-type: none"> <li>- Facility Planning</li> <li>- General application of covering models</li> <li>- Model comparison</li> <li>- Integration of more realistic assumptions</li> <li>- Integration of a Gradual Decline Model</li> </ul>
<b>Application</b>	<ul style="list-style-type: none"> <li>- Mathematical / Statistical investigation</li> <li>- In-depth analysis of covering model generalisations</li> </ul>
<b>Theory</b> Framework	<ul style="list-style-type: none"> <li>- Gradual cover model</li> <li>- Cooperative cover model: all models contribute to demand coverage</li> <li>- Variable radius model</li> </ul>
<b>Strengths</b>	<ul style="list-style-type: none"> <li>- In-depth mathematical investigation</li> <li>- Definition of three key improvement areas</li> <li>- Model revision to identify general, systematic shortcomings</li> <li>- Integration of decay function</li> </ul>
<b>Limitations</b> Weaknesses	<ul style="list-style-type: none"> <li>- Theoretical modelling</li> <li>- Missing integration of supply data</li> <li>- No reference to process sequencing</li> <li>- Discrete modelling</li> </ul>

<b>Recommendations</b> and implications	<ul style="list-style-type: none"> <li>- Investigate solution approaches to network location</li> <li>- Develop continuous model</li> <li>- Integrate variable radius model</li> <li>- Integrate weighted fractional demand</li> </ul>
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Table 2-9: Critique worksheets Berman, Drezner and Krass (2010)

Source: Author

### 2.6.3 Model C – Optimal Location Charging Station Model

Frade et al. (2011) focus in their model for Optimal Location of Charging Stations (OLCSM) on the implementation of electric charging stations for electric vehicles within a defined city limit. The model, as later also referred to by Giménez-Gaydou et al. (2016), is based on MCLM in reference to Level 2 charging with single or multiple refuelling periods per day.

Demand for recharging is roughly estimated, whereas OLCSM, in contrast to the previously explained models, defines demand as a stationary demand which represents a function of possible charging times instead of vehicle routes. Therefore parking spaces in industrial and residential areas are defined as implementation spots in this discrete modelling approach. Full recharging is estimated to be necessary every three days in order to cope with EV range requirements.

Basic assumptions for charging station allocation modelling are made over the course of four steps. The first step defines the total number of facilities to be installed. The second step identifies possible implementation spots  $K$  for discrete modelling. The third step defines the maximum capacity of charging stations for capacitating the simulation. The fourth step defines the maximum and minimum range for coverage.

The basic OLCSM under the assumption of a cumulative demand according to Frade et al. (2011) is formulated as per below:

$$\max \sum_{j \in J} \sum_{k \in K} n r_{jk} u x_{jk} - \sum_{k \in K} 0.01 \cdot s_k \quad (17)$$

$$s.c. \quad \sum_{k \in K} x_{jk} \leq 1 \quad \forall j \in J \quad (18)$$

$$x_{jk} \leq r_{jk} y_k \quad \forall j \in J; k \in K \quad (19)$$

$$\sum_{k \in K} y_k = p \quad (20)$$

$$z_k \geq \sum_{j \in J} u x_{jk} \quad \forall k \in K \quad (21)$$

$$s_k \geq \frac{z_k}{n} \quad \forall k \in K \quad (22)$$

$$x_{jk}, z_k, s_k \geq 0 \quad \forall j \in J; k \in K \quad (23)$$

$$y_k \in (0,1) \quad \forall k \in K \quad (24)$$

The target function (17) expresses the maximisation of demand coverage, with  $u$  being the number of chargers for refuelling;  $n$  as the number of refuelling operations;  $r_{jk}$  as the level of coverage in reference to covering distance;  $x_{jk}$  as the proportion of users from the demand spot  $j$  by a facility located in  $k$ ;  $y_k$  being 1 or 0 in reference to a charging station being located in  $k$ ;  $p$  as the number of facilities;  $z_k$  the capacity for recharging of a facility in  $k$ ;  $s_k$  as the number of supply points of a charging station in  $k$  as additional feature of this capacitated model (22).

Side condition (18) limits recharging to a maximum of 100%. (19) presents the level of coverage by the installed number of stations, which is defined by constraint (20). Constraint (21) refers to charging station capacities that are available on demand. Side conditions (23) and (24) define the parameter values.

OLCSM focuses on the usage of charging station allocations that are within acceptable range of break spots that occur due to the driving behaviour of EV users. This approach integrates existing downtimes into the consideration of increased equipment availability in order to facilitate minimal disturbance of processes and increase overall efficiency, whereas process sequences and by this process data are not considered.

The energy demand of electric vehicles is roughly estimated based on the assumption that available battery energy is sufficient for three days of driving with an approximated maximum range of 60km, whereas energy consumption is not numbered and evaluated. In addition to this, Gonzalez et al. (2014:648) criticise the range requirements to be based on an estimation of the real mobility behaviour, so that driving process sequences are also neglected.

Within this model, increased focus is given to the supply of electric energy to the investigated fleet of electric vehicles. Level 2 charging with 2kW to 3kW of transmission performance, as well as the capacitated approach integrate the requirements of energy supply which is neglected by most of the investigations in this

field of research. Jin (2016:19) highlights this increased accuracy of the model's assumptions and estimations in this field of research for increased result reliability.

The aspects of OLCSM with impact to the pursued research approach is the definition of charging station allocation in reference to stationary demand based on the potentials of spots close to work or living areas such as parking lots with a high fraction of downtimes, whereas the potentials of these spots are not evaluated, but roughly assumed. The consideration of process related downtimes for recharging goes in line with the requirements of occasional recharging, whereas these potentials need to be determined and integrated into process sequencing.

The major limitation of OLCSM is the rough and vague estimation of demand (Frade et al. 2011:97). Refuelling times are considered to be existent within the investigated three-day periods for recharging, with the result that sequencing of operating and break periods is neglected. Furthermore, Jin (2016:19) addresses the limitation of OLSCM to refer to estimated vehicle characteristics, so that the evaluation of energy consumption and supply potentials allows the generation of approximated results only. A further weakness is the fixed and predefined covering range limitation based on a maximum range. In this regard, covering distance is no decision variable as a function of additional energy input, so that the possible positive contribution of demand spots outside of the defined range to the energy balance is neglected. The recommendations for future research as given by Frade et al. (2011) as well as the model overview are depicted in Table 2-10.

<p><b>Research Context</b></p> <p>Purpose of the study</p>	<ul style="list-style-type: none"> <li>- rEV Mobility Program</li> <li>- Development of a charging station planning strategy</li> <li>- Increased efficiency in energy consumption and ecology</li> <li>- Decreased cost of fuel consumption</li> <li>- Maximisation of demand coverage</li> </ul>
<p><b>Application</b></p>	<ul style="list-style-type: none"> <li>- Road electric vehicle</li> <li>- Case study application on statistic data</li> </ul>
<p><b>Theory</b></p> <p>Framework</p>	<ul style="list-style-type: none"> <li>- Maximum covering location model</li> <li>- Flow interception model</li> <li>- Fixed cover distance</li> <li>- Discrete modelling</li> <li>- Repeated simulation runs as validity proof</li> </ul>

<b>Strengths</b>	<ul style="list-style-type: none"> <li>- Integration of driving patterns</li> <li>- Focus on efficiency and ecology</li> <li>- Reference to energy consumption</li> </ul>
<b>Limitations</b> Weaknesses	<ul style="list-style-type: none"> <li>- Based on demand estimations</li> <li>- Fixed covering distance</li> <li>- Discrete modelling on forecasted supply nodes</li> <li>- Based on average vehicle range demand and energy consumption</li> <li>- Flow interception model less applicable for static demand coverage</li> </ul> <p style="margin-left: 20px;">Optimisation</p>
<b>Recommendations</b> and implications	<ul style="list-style-type: none"> <li>- Execution of benefit-cost analysis</li> <li>- Reference to battery technology developments</li> <li>- More detailed demand investigations such as break times, processes and range demand</li> </ul>

Table 2-10: Critique worksheet Frade et al. (2011)

Source: Author

#### 2.6.4 Model D – Simulation-Optimisation Model for Charging Infrastructure

The Simulation-Optimisation Model for Charging Infrastructure (SOMCI) of Xi, Si-shansi and Marano (2013) determines the allocation of electric vehicle chargers in order to maximise the use rate of the charging facilities by referring to a combined implementation of Level 1 and Level 2 chargers. The research highlights the negligence of fuelling time durations within most existing approaches of charging station allocation and develops a discrete model based on the consideration of long-time parking lots for EV.

The integration of realistic driving patterns of EV is a central aspect of this approach, meaning that in a first step the volume of EV flows is determined. In contrast to this, Bi et al. (2016:336) criticise the reference of the model to forecasted Origin – Destination pairs only instead of integrating real-world trip data. In a second step, this data is integrated into a simulation model in order to determine the number of vehicles that can be charged by the potential charging sites. The finalising step determines the charging allocation and capacity of charging stations.

The basic SOMCI model as per Xi, Sioshansi and Marano (2013) is formulated as:

$$\max \sum_{j \in J} \sum_{g \in G} f_j(h_j^g) \quad (25)$$

$$s.c. \quad h_j^g \leq A_j^g \cdot \sum_{v \in V: N_{v,j} > 0} 1 \quad \forall j \in J; g \in G \quad (26)$$

$$\sum_{g \in G} A_j^g \leq 1 \quad \forall j \in J \quad (27)$$

$$h_j^g \in \mathbb{Z}^+ \quad \forall j \in J; g \in G \quad (28)$$

$$A_j^g \in (0,1) \quad \forall j \in J; g \in G \quad (29)$$

$G$  defines the set of available charging technologies. The amount of recharged energy in location  $j$  by  $h_j$  chargers and the charging rate  $r$  is given by  $f_j$ .  $V$  represents the number of EV.  $N_{v,j}$  counts the number of approaches of vehicle  $v$  to the station in  $j$ . The binary variable  $A_j^g$  equals 1 if a type- $g$  charger is allocated in  $j$ , 0 otherwise.

The target function (25) maximises the number of charging EV. Side condition (26) allows the implementation of type- $g$  chargers in  $j$  only and (27) to have one charger type in each location only. (28) and (29) defines the possible values of the decision variables.

SOMCI bases the execution of location-allocation modelling on process simulations in order to improve the integration of electric charging facilities. The strong reference to energy supply based on Level 1 and Level 2 charging fosters efficiency and resource allocation within the investigation field (Jing et al. 2016:2).

Energy consumption patterns are roughly integrated by the reference to EV average efficiency, which is measured in kWh of battery energy being used per km driven, whereas the numbers are stated to be based on estimations (Ahn and Yeo 2015:2, Shahraki et al. 2015:166).

SOMCI suggests that EVs pass by the set of stations to be implemented on their simulated routes and can approach at any time, so that sequencing of process patterns is neglected. For the charging station allocation, the model simulates the number of vehicles that can be recharged with no reference to additional time



and distance efforts (Lindgren and Lund 2015:1). The focus lies on the maximisation of utilised capacity but neglects the maximisation of recharged energy for individual vehicles as charging times and usable break times are no integral part of the investigations. Besides of their reference to more realistic driving behaviour, Xi, Sioshansi and Marano (2013) recommend the integration of more realistic data and the execution of several simulation runs in order to validate model design (see also Table 2-11).

<b>Research Context</b> Purpose of the study	<ul style="list-style-type: none"> <li>- Simulation optimisation model to determine EV chargers to maximise use by private owned EV</li> <li>- Combined integration of Level 1 and Level 2 chargers</li> <li>- Investigation of interactions of optimisation criterion</li> </ul>
<b>Application</b>	<ul style="list-style-type: none"> <li>- Maximum covering location model</li> <li>- Simulative integration of Level 1 and Level 2 chargers</li> <li>- Case study simulation</li> </ul>
<b>Theory</b> Framework	<ul style="list-style-type: none"> <li>- Battery energy maximisation calculation for increased recharge energy</li> <li>- Linear integer programming</li> <li>- Result validation by sensitivity analyses on several simulation runs on alternating input data</li> </ul>
<b>Strengths</b>	<ul style="list-style-type: none"> <li>- Real case study application</li> <li>- Integration of specific technical performance data</li> <li>- Reference to fuelling times</li> <li>- Integration of fractional demand</li> <li>- Tour-record data available for individual vehicles</li> </ul>
<b>Limitations</b> Weaknesses	<ul style="list-style-type: none"> <li>- Vehicle data assumed and standardised</li> <li>- Based on probabilistic drive patterns</li> <li>- Reference to a fixed study region</li> <li>- Discrete modelling</li> </ul>
<b>Recommendations</b> and implications	<ul style="list-style-type: none"> <li>- Integration of individual tour-record data, i.e. process sequence data</li> <li>- Execute several simulation runs on alternative input data for validation</li> </ul>

Table 2-11: Critique worksheet Xi, Sioshansi and Marano (2013)

Source: Author

### 2.6.5 Model E – Charging Station Covering Model

The target of the approach by Giménez-Gaydou et al. (2016) is to simultaneously maximise demand coverage and charging station utilisation, which results in the

constraints for increased efficiency and effectiveness being fulfilled. The Charging Station Covering Model (CSCM) targets on the optimal location of battery electric vehicle charging stations being based on MCLM and by this being an advancement of the OLCSM approach by Frade et al. (2011) and Berman, Drezner and Krass (2010) according to subsections 2.6.1 and 2.6.2. It is an uncapacitated gradual maximal covering model with consideration but no special attention to energy supply characteristics.

The executed approach consists of four stages. The first stage includes the definition of BEV charging needs in reference to existing storage and charging systems and estimated driving patterns in order to define the daily average charging needs. The second step evaluates the demand satisfaction by investigating charging station accessibility and determining potential charging spots in line with discrete modelling. The third step focuses on the total demand to be covered and the fourth step combines the previously described information into an optimisation model.

The innovative feature of CSCM in comparison to the displayed models is the extension of the discrete sites for charging station implementation  $j$ , so that the set of possible locations  $J$  converges towards a continuous model.

Given that CSCM is based on the model formulations as per subsection 2.6.1, the detailed calculation specifications can be disregarded at this point. The contribution of CSCM to the pursued research approach refers to continuous modelling in order to define the optimal charging station allocation in reference to the overall system energy balance. Furthermore, CSCM integrates the weighting factor  $w_{ij}$  that defines the proportion of parking time being available for battery charging. This perspective on charging time as a constant factor in reference to individual demand spots puts the contribution of individual vehicles to the overall system energy balance into the focus of investigations among the other implications to future research as per Table 2-12.

<b>Research Context</b> Purpose of the study	<ul style="list-style-type: none"> <li>- Location of BEV charging station in urban areas</li> <li>- Investigation on the potential to satisfy EV charging demand</li> </ul>
<b>Application</b>	<ul style="list-style-type: none"> <li>- Uncapacitated Maximal Covering Location Model</li> <li>- Case study on BEV and charging station integration</li> </ul>
<b>Theory</b> Framework	<ul style="list-style-type: none"> <li>- Maximisation of weighted charging needs</li> <li>- Fixed covering distance</li> </ul>
<b>Strengths</b>	<ul style="list-style-type: none"> <li>- More detailed analysis of BEV charging needs</li> <li>- Reference to different charging technologies</li> <li>- Integration of technical performance indicators</li> <li>- Focus on charging network (instead of individual spots)</li> </ul>
<b>Limitations</b> Weaknesses	<ul style="list-style-type: none"> <li>- Energy requirements not based on vehicle specifications</li> <li>- Estimated charging needs</li> <li>- Discrete model</li> <li>- Uncapacitated approach</li> <li>- Fixed covering distance</li> </ul>
<b>Recommendations</b> and implications	<ul style="list-style-type: none"> <li>- Integration of weighted charging need (time fractions for charging)</li> <li>- Charging station capacity of minor impact to station location</li> <li>- Combination of charging spots into a network</li> <li>- Gradual decrease of cover rate with increasing distance</li> <li>- Usage of real case data</li> <li>- Apply to real case</li> </ul>

Table 2-12: Critique worksheet Giménez-Gaydou et al. (2016)

Source: Author

## 2.7 Main important factors of charging station allocation models and frameworks

The executed study of existing models and methodologies in the field of location-allocation and charging station allocation for electric vehicles highlights the main components and factors to be considered for the application of a framework for occasional recharging of non-road electric vehicles. The executed analysis of available models and formulations concluded that most of these models contain similar factors in order to develop their models and frameworks, whereas the difference among these models in integrating these factors is the quality and the definition of underlying sub-elements and components. These factors can be defined and described as:

- *Demand Definition* defines the demand to be covered as whether being dynamic or static. Dynamic demand is used in investigations that base charging station allocation on vehicle and process routing. By using a static demand definition location determination refers to the occurrence of break times. As such, the number and duration of breaks represent the demand.
- *Demand Modelling* refers to the demand volume being identified by a probabilistic, stochastic distribution or by deterministic measurements and monitoring.
- The *Spatial Representation* specifies  $J$  as being the set of possible locations for a defined number of facilities to be implemented. In discrete modelling  $J$  is limited to a pre-defined set of allocation spots. Continuous modelling in contrast allows facility allocation in any spot according to the research design within the defined investigation area within  $(x_{\min}; y_{\min}) \cup (x_{\max}; y_{\max})$ .
- *Process Sequencing* defines the chronology and geographic determination of processes, so that break times and durations as well as their location within the defined investigation area are determined. Undefined models integrate charging whenever vehicles pass by a charging site. Charging durations, as well as points are assumed to be available at any time.
- *Energy Consumption* integrates energy consumption data into the investigations, whereas this data can be based on roughly estimated or accurate values.
- *Energy Provision* refers to the consideration of energy supply characteristics within the respected investigation such as charging level, transmission performance and/or transmission efficiency. Figures can be based on approximated or accurate data.
- *Covering Distance* is the maximum (additional) travel distance or time, which determines a demand spot to be captured or not. The covering distance can be pre-determined by definition (exogenously) or by its expression as a function as a decision variable (endogenously). The reference of a model to an endogenous covering distance also implies the consideration of fractional or partial demand.

The executed literature review and the identified shortcomings of previous research, i.e. the recommendations for further investigations, form the basis for the development of a target model which is based on these findings in reference to the research environment requirements. The research recommendations given within the reviewed models and frameworks are the result and contribution of previous research as illustrated in Table 2-13.

Factors	Target Model	Recommended by
1. Demand definition	static	Berman, Drezner and Krass 2010 Gonzalez et al. 2014 Giménez-Gaydou et al. 2016
2. Demand modelling	deterministic	Frade et al. 2011 Ahn and Yeo 2015
3. Spatial representation	continuous	Berman, Drezner and Krass 2010 Upchurch, Kuby and Lim 2009 Liu and Sun 2014
4. Process sequencing	yes	Upchurch, Kuby and Lim 2009 Frade et al. 2011 Xi, Sioshansi and Marano 2013 Giménez-Gaydou et al. 2016
5. Energy consumption	accurate	Upchurch, Kuby and Lim 2009 Giménez-Gaydou et al. 2016
6. Energy provision	accurate	Xi, Sioshansi and Marano 2013 Eiselt and Marianov 2015 Jin 2016
7. Covering distance	endogenous	Berman, Drezner and Krass 2010 Liu and Sun 2014 Giménez-Gaydou et al. 2016

Table 2-13: Research recommendations

Source: Author

Table 2-14 shows the comparison of the investigated models based on the defined factors with relevance to model design. The classification is based on the above executions. Referring these factors to the research environment parameters as identified and defined within the literature review (see Table 2-5 [p.29]), the factors 1 to 4 integrate process characteristics and data. Factor 5 refers to energy consumption data and the factors 6 and 7 to energy supply.

Factors	FRLM	GCM	OLSCM	SOMCI	CSCM	Target Model
1. Demand definition	dynamic	static	static	dynamic	static	static
2. Demand modelling	probabilistic	probabilistic	probabilistic	probabilistic	probabilistic	deterministic
3. Spatial representation	discrete	discrete	discrete	discrete	discrete	continuous
4. Process sequencing	none	none	none	yes	none	yes
5. Energy consumption	estimated	estimated	estimated	estimated	estimated	accurate
6. Energy provision	approx.	approx.	accurate	accurate	approx.	accurate
7. Covering distance	exogenous	endogenous	exogenous	exogenous	exogenous	endogenous

Table 2-14: Comparison of available location-allocation models for charging station allocation

Source: Author

From Table 2-14 it can be concluded that existing models contain shortcomings in their applicability for investigations in the defined field. In order to overcome the identified limitations of the reviewed models, a framework and location-allocation model for the potential evaluation of occasional recharging in production related material handling needs to be developed that addresses the identified criteria in reference to the investigated and defined requirements of the research project environment. This model needs to be established on the findings of the reviewed frameworks, to integrate and combine the recommendations by previous research approaches, so that the following research objectives were deduced.

## 2.8 Chapter summary

In reference to existing models and frameworks, as well as the research target and the requirements of identified research components, the chapter summary identifies and highlights the gap in research and literature that this research project aims to fill.

As shown in the comprehensive literature review, several concepts for charging station allocation for rEV have been introduced in literature and by this highlight the importance of effective charging station integration. From the critique of existing models it can be concluded that these do not (fully) address the requirements of occasional recharging of non-automated nrEV, so that for the analysis of potentials for increased efficiency and sustainability, a new framework and location-allocation model needs to be developed.

Existing models on location-allocation and charging station allocation are based on discrete modelling, meaning that the set of locations is pre-determined by definition. In a rEV environment, discrete modelling decreases linear programming complexity and refers its allocation to strategic spots in order to increase usage and operating hours of charging stations. As a gap within the design of existing models and as a requirement of the research environment, a dedicated model has to change the perspective of investigations from charging stations and the ratio of usage to the energy balance of individual vehicles, respectively the fleet of vehicles in order to evaluate the potential for increased system efficiency. The reference to contactless charging stations for occasional recharging enables the implementation in almost the entire surface of a production facility, so that discrete modelling does not contribute to the most effective allocation in this application as the charging station allocations are predetermined by researcher's choice.

The perspective of existing approaches to charging station allocation being based on independent routing optimisation or static demand coverage has to be changed towards a process sequence based optimisation in order to integrate process sequences to increase overall system and process efficiency. This changed perspective to qualitative integration of sequences, i.e. value adding and non-value adding process characteristics, instead of routes as well as individual quality as weighting factor of demand spots for charging station allocation form a new approach in this field of research.

The executions and results of the literature review reveal the gap in scientific research in reference to charging station allocation for occasional recharging in production related material handling. Whereas there is abundant research dealing with charging station allocation for rEV, there is none for nrEV in the described research environment. The executed research project addresses this gap and develops a framework and model in order to foster knowledge about charging station allocation for occasional recharging in production related material handling and the potentials that emerge due to the system integration. The design of this model for occasional recharging has to enable its general application in respect to the availability of required data and therefore presents a first reference model for further investigations.

The investigated approaches in reference to rEV charging station allocation served as guidance for the further research progress and the executed literature review produced several aspects that are subject to integration in the development of a designated, new model. Consequently the pursued framework has to include

- (1) a MCLM based approach for potential analysis
- (2) the integration of more realistic assumptions
- (3) accurate data on energy supply and consumption
- (4) a function based covering radius that integrates energy consumption
- (5) the integration of characteristics of occasionally occurring break times as fractional charging potential
- (6) process sequencing
- (7) a calculation model to evaluate possible resource savings and its meaning to increased sustainability

To ensure practical framework applicability, as well as the appropriateness of data taken as basis for simulation and analysis execution, the collection of energy consumption and process data from applied material handling processes and functions can be regarded an imperative investigation component. Hence, data collection in real application constitutes a milestone in the development of a reliable data source in order to present a first reference model for further investigations. This target creates the need for collaborative monitoring and investigations of science and industry. The research execution of corresponding energy consumption data and process data collection are explained within the sections 4.2 [p.89] and 4.3 [p.100].

The subsequent chapter presents the adopted methodology in order to address the shortcomings, limitations and recommendations of earlier research, as well as to achieve the identified aims and objectives of the pursued research approach.



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# CHAPTER 3

## METHODOLOGY

### 3.1 Introduction

As per the definition of Redman and Mory (1923:10), research is a ‘systematized effort to gain new knowledge’ and in combination with the definition of research as ‘the strategy or architectural design by which the researcher maps out an approach to problem-finding or problem-solving’ (Buckley, Buckley and Chiang 1976:1) it becomes evident, that developing research is strongly connected to a systematic approach. In this way, the used research methodology can be described as the ‘way to systematically solve the research problem’ (Kothari 2004:8).

The outline of the research methodology constitutes the sound and robust investigation framework which includes information on the model choice as well as the operation of data collection and data analysis. As a basis for the deduction of reliable conclusions, the framework justifies the approach taken and solidifies the associated research findings (Creswell 2009). Thus, the target of the developed research methodology and design is to establish the theoretical framework in order to address the subject specific requirements. In doing so, the research results introduce innovative knowledge and aspects to the field of charging station allocation.

The pursued research establishes new insights for researchers and practitioners in the field of electric charging station allocation being based on previous studies which showed limitations towards their applicability for charging station allocation in industrial environments and occasional recharging, as well as in respect to their integration of and reference to reliable and accurate process, energy consumption and supply data.

The following sections explain and justify the adopted research approach as well as its methodology. Prior to defining the executed research design, the underlying hypothesis and connected research questions will be clarified. Based on these

fundamentals, appropriate research methods need to be selected that address the research target in order to draw clear and reliable deductions from the data collected (Saunders, Lewis and Thornhill 2009:32).

### **3.2 Research Questions and Hypothesis**

The hypothesis of the pursued research approach is formulated, so that the process-based integration of contactless power transfer systems for occasional recharging of industrial truck batteries in the allocation(s) of the highest volume of additional recharge energy creates the potential for increased efficient and sustainable system solutions.

The determination of the spot(s) of highest recharge energy, respectively highest concentration of process based idle times depends on the definition of the model covering distance with impact to idle time relocation as per subsection 5.2.3.3 [p.119] and process factors which impact the volume of recharge energy such as vehicle velocity, vehicle energy consumption, charging performance and the arrangement of usable idle times (see subsection 2.4 [p.26]).

The target of the pursued research is to answer the following research questions:

Q1: What are the key performance indicators in production related nrEV material handling?

Q2: How can optimised charging station allocations be calculated?

Q3: Which KPI are available for charging station allocation?

Q4: How can these KPI be integrated in location-allocation modelling?

Q5: What is the potential of occasional recharging in production related nrEV material supply?

Q6: How can these potentials contribute to increased efficiency and sustainability?

The above mentioned research questions, as well as the overall hypothesis, focus on the integration of contactless power transfer systems for occasional battery charging in production related material handling on nrEV, whereas the focus lies on the determination of optimised charging station allocation and the resultant

impact to the systems energy balance. The analysis of inherent process interruptions for additional energy input and their potential for sustainable system improvement, as well as the development of a designated location-allocation model are the key objectives of the pursued research project. Addressing this gap in scientific research will provide the contribution to knowledge of the executed research project.

### 3.3 Objectives

As highlighted within the previous section, individual models and frameworks tackle different aspects of the pursued research environment but lack a comprehensive combination of impact factors, as well as data accuracy. In particular, the lack of combined and integrated investigations emphasises the importance for the development of a dedicated framework. In line with the evaluation by Frade et al. (2011), Giménez-Gaydou et al. (2016) and fostered by the executed review of existing models and the described requirements of the research environment to the application of a framework based location-allocation model, a Maximal Covering Location Model is evaluated to be most suitable to be applied for the pursued research approach. Location-Set-Covering-Models target on total coverage of demand, whilst the pursued approach focuses on the optimal and most efficient charging station integration as being a function of resources and cost, so that a limited number of stations with no target to total coverage needs to be implemented.

This leads to the development of a dedicated location-allocation model which integrates process, consumption and supply data in order to provide a scientific and standardised framework to analyse material handling processes and to identify and evaluate potentials of the technology implementation for occasional recharging.

For the effective realisation of the research aims as per section 1.2 [p.6], the following objectives have been identified:

- (1) To develop a generally applicable framework for production related material handling that integrates all relevant performance indicators into a specific location-allocation model and that provides recommendation for optimisation approaches

- (2) To integrate technology based characteristics with impact to the performance evaluation
- (3) To integrate and investigate lean and green aspects of the technology implementation
- (4) To execute case study based performance analyses to foster the understanding of CPT operations, cost-benefits and performance trade-offs
- (5) To evaluate the potentials of occasional charging for increased system efficiency and sustainability

### **3.4 Research Design**

The research design describes the framework of a pursued research project and can therefore be defined as its overall plan (Robson 2002). According to Saunders, Lewis and Thornhill (2009:137), research design performs the function of clarifying the research objectives as well as structuring the research process from hypothesis to a proven theory in order to generate a consistent and reliable research approach. The research design includes and provides the justification of the tactics and decisions taken within research execution, so that the methodological approach certifies research credibility and validity (Blaikie 2010).

The illustrated research design forms the theoretical framework for the investigation and evaluation of a process-based integration approach of contactless energy provision in reference to occasional recharging in intralogistics material handling. The results of the research introduce new knowledge in the field of occasional recharging and location theory to researchers and practitioners based on previous findings and studies, which showed limitations either due to unavailability of adequate data or due to deficient studies conducted in dissimilar research environments.

In reference to the research questions as per section 3.2 the pursued research project design is subdivided into three consecutive research phases, RP I to RP III (see Figure 3-1). The execution of a comprehensive literature review in reference to the research environment and the scientific landscape of existing models of Research Phase I was discussed within chapter 2. Existing literature and research results form an important basis of information in order to answer the de-

financed research questions Q1 and Q2; Research Phase II deals with detailed investigations of the real research environment in reference to the research subject by answering Q3 and Q4. The result of RP II, as the data collection phase, is a comprehensive data base of subject related information. Data is formatted and edited for its integration into a simulation model in order to identify and evaluate the potential within RP III for answering research questions Q5 and Q6.

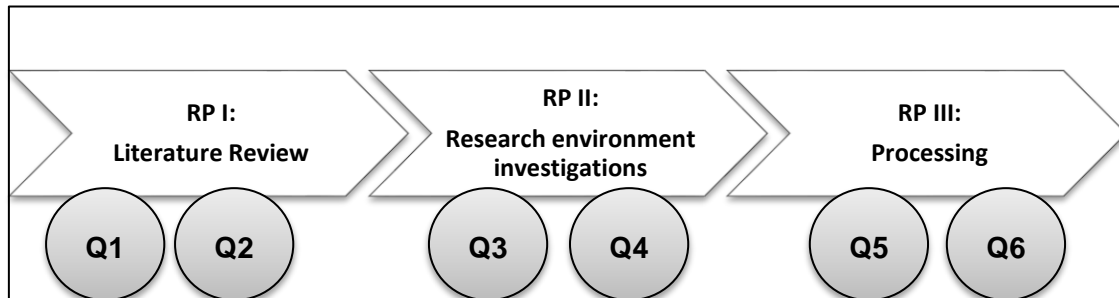


Figure 3-1: Research question investigation phases  
Source: Author

In line with the explanations by Saunders, Lewis and Thornhill (2009), each research phase needs to be defined in reference to its individual research purpose, approach, method, strategy and content in order to execute a systematic and structured research process. Figure 3-2 illustrates the components of the research design in reference to the defined research phases.

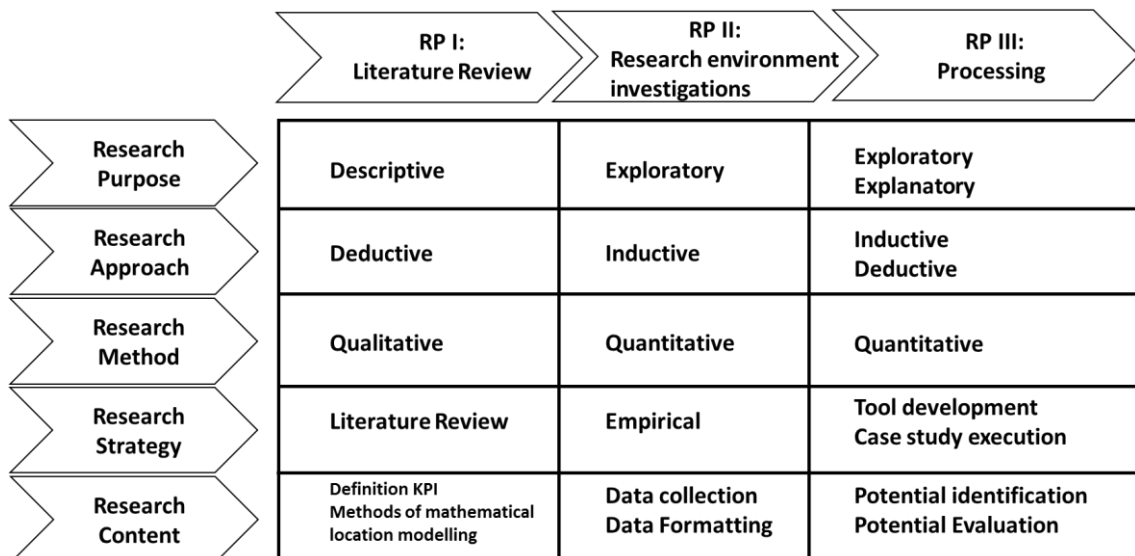


Figure 3-2: Project research design  
Source: Author

The following passage of chapter 3 elucidates the different aspects of the research design and its application to the pursued research. Subsection 3.4.6 [p.78] shows the differences in contents, reviews the individual research phases and by

this explains the contribution of each phase to answer the defined research questions.

### **3.4.1 Research Purpose**

The goal of the research purpose is to define the project objective, i.e. the way to realise the research target. According to Saunders, Lewis and Thornhill (2009:139) scientific literature differentiates among descriptive, exploratory and explanatory research purposes, whereas Robson (2002) points out the existence of mixed approaches as well as the potential need to change the research purpose over time.

The target of descriptive studies is to detect, define and describe the present state of affairs in an investigated field by considering influencing factors (Kumar 2011:12). Its target is to collect data which clarifies 'the who, what, when, where and how of a topic' (Cooper and Schindler 1998:141) in order to generate an overview of events and situations (Robson 2002:59). In an *ex post facto* descriptive approach, parameters and conditions cannot be manipulated or changed by the researcher, so that the resulting data presents a report on a constant factor basis (Cooper and Schindler 1998:132). In general, *ex post facto* descriptive approaches focus on the collection of data by measuring and monitoring processes and items by referring to different kinds of surveys (Kumar 2011:7). The target of descriptive studies is to generate a clear and accurate overview on the research subject (Robson 2002:59). In this way it can also be considered as a prefixed data collection part for exploratory or explanatory studies (Saunders, Lewis and Thornhill 2009:138).

Exploratory studies refer to clarifying 'what is happening; to seek new insights; to ask questions and to assess phenomena in a new light' (Robson 2002:59). Therefore, it is used in order to increase the understanding of a subject by generating a broad set of data which by processing narrows and leads to more knowledge (Churchill and Jacobucci 2010). According to Kumar (2011:11), a positive side effect of exploratory research is the development, testing and/or re-assembling of measuring tools, equipment and/or procedures. Being based on the outcome of the generated data, explorative studies possess high flexibility but do not implicitly lead to a less structured procedure (Saunders, Lewis and Thornhill

2009:140). According to the definition by Kumar, explanatory studies try to determine the interdependencies of parameters and variables (Kumar 2011:12). Therefore, the target is to explain 'why' something happens and to what extent interrelations can be located and explained (Saunders, Lewis and Thornhill 2009:141).

Location-allocation modelling focuses on the determination of optimised facility implementation and by this involves the integration of all limiting factors and parameters (Berman, Drezner and Krass 2010). In line with the explanations by Robson (2002:59) and Saunders, Lewis and Thornhill (2009:138), this highlights the need for a descriptive research section which investigates and identifies the components of a dedicated location-allocation model as a preparation step to the research investigations and reviews existing models in reference to their research project applicability. Upchurch, Kuby and Lim (2009) note that the results of location modelling are subject to further analysis and evaluation towards its target achievement in line with an exploratory and explanatory research approach.

The executed literature review of Research Phase I is attributed to be of descriptive nature. The comprehensive analysis of existing literature in the described field of studies defines the research environment based on available scientific resources, while the comparison and review of available location-allocation models identified the gap in research. In contrast to this, RP II explores the research environment, collects relevant data based on previous findings, ensures adequate quality of data and formats this data in order to integrate this information into a comprehensive analysis. Although there is knowledge and also data available in this field of investigations, RP I highlighted the lack of quality and accuracy of data, so that dedicated investigations for example in the field of energy consumption address this general shortcoming. This accurate and target oriented data forms the basis for the impact analysis and evaluation of the potential of occasional recharging, being the subject of the simulations of Research Phase III. This phase is a mixed approach of exploratory and explanatory nature (Creswell 2009, chapter 4 [p.89] and chapter 6 [p.144]). The potential for resource savings based on collected process and energy data is subject to be explored in order to evaluate the impact to system design. In a second step, the results and

potential needs to be explained in order to foster knowledge about the impact factors.

### 3.4.2 Research Approach

Formal research approaches are differentiated between two types of scientific problem solving – deduction and induction. According to Trochim (2006), deduction refers to testing a theory while the process evolves from the general and leads to the specific. Conversely, induction aims to build a single or a set of theories and tries to lead from the specific to generalisations (Saunders, Lewis and Thornhill 2009:124-126). Answered questions refer to the ‘which, where, who, whether, how and what?’ (Buckley, Buckley and Chiang 1976:3). As shown in Figure 3-3, the starting point of a deductive approach, i.e. a general principle or theory, is the result of induction, whereas also combined or circular variations exist.

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Figure 3-3: Deductive and inductive research approach  
Adapted from Trochim (2006) and Saunders, Lewis and Thornhill (2009)

The initial step of designing a deductive research approach is to generate a theory-based hypothesis, which by the following steps needs to be verified or falsified. In order to test the developed hypothesis, subject specific data needs to be collected. Specifying a tested way of measuring and monitoring these parameters is an essential component of this structured research approach (Robson 2002). Testing the hypothesis is backed by the collected and analysed data, and leads



to confirmation or disconfirmation of the hypothesis (Trochim 2006). In order to prove the veracity of a hypothesis, there is the demand for proven validity and reliability of the underpinning data (Saunders, Lewis and Thornhill 2009:14), what can be achieved by referring to repeatable, highly structured methods (Gill and Johnson 2002). Reducing the problem to the simplest possible elements reduces the complexity of the research subject and leads to increased knowledge about the investigated research factors (Saunders, Lewis and Thornhill 2009:125). The concluding step of deduction is to generalise its findings into regularities. Therefore, it is often linked to quantitative data collection in order to endorse the theory through a sufficient amount of data (Saunders, Lewis and Thornhill 2009:124-127).

The opposed approach of induction focuses on generating a theory based on an undefined number of facts in order to improve the understanding of a problem's nature (Saunders, Lewis and Thornhill 2009:126). From specific observations generally applicable regularities shall be derived in order to formulate a tentative hypothesis. This hypothesis needs to be analysed towards its significance to generate a valid theory (Cooper and Schindler 1998:31-33). Inductive approaches majorly use qualitative data in order to investigate the relationship of reason and conclusion (Saunders, Lewis and Thornhill 2009:126).

In line with the research project attribution to be of descriptive, exploratory and explanatory character, the research project sequencing asks for a circular combination of deduction and induction approach as seen in Figure 3-4. Research Phase I is based on a deductive approach. The hypothesis is developed based on existing theories as explained in the comprehensive literature review which illustrates fundamental performance indicators and its dependencies. The collection of energy data in RP II forms the basis for the execution of energy based simulations and data evaluation of RP III. RP II as being of inductive nature focuses on the determination of data and parameter dependencies in order to generate valid and reliable results. As RP III focuses on the quantitative processing of the results of the conceptual model, it can be classified as a deductive research part, so that the research approach can be classified as being a mixed approach.

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Figure 3-4: Combined research design approach  
Adapted from Haider and Birley (1999)

### **3.4.3 Research Method**

The pursued research study which is based on the process integration of a new charging technology with its own technology characteristics focuses on optimised charging station allocation. This involves the researcher in the development of a dedicated framework and a comprehensive plan for the realisation of the research, the choice of an appropriate research method being employed for data collection, the compliance with ethical principles within all stages of the research project, and the use of appropriate data analysis methods in order to accomplish the research aims and objectives.

Research methods can be distinguished to be of qualitative or quantitative nature. Qualitative methods are majorly used in inductive approaches targeting to build

theories, to analyse complex data in order to interpret observation results and to understand the facts of a case (Taylor 2005, Newman and Benz 1998, Jackson 2011). Quantitative methods are used to test and confirm theories based on a larger number of numerical data (Saunders, Lewis and Thornhill 2009:151). Mixed approaches are gaining importance and acceptance in order to combine the advantageous aspects of both approaches so that these comprise a valid basis for a research project (Bryman and Bell 2007, Saunders, Lewis and Thornhill 2009).

Kumar (2011) defines qualitative research as more unstructured research method which is employed to generate a theory, so that it is particularly useful for inductive approaches. As the number of considered data is lower than for quantitative research, it is regarded as more subjective considering it refers to the researchers choice and therefore involves researcher's preferences (Bryman and Bell 2007:28). Van Maanen highlights the target of qualitative research to describe, decode and explain the nature of research phenomena (Van Maanen 1979:520), so that it can also be interpreted as an integral part of data formatting and verification.

A quantitative approach focuses on testing theories, so that it is often used within deductive research (Bryman and Bell 2007:28). While proving or disproving theories and hypotheses, it is distinguished as a highly analytical and structured method (Kumar 2011:8). Quantitative studies aim to proceed the research by generating a vast number of convincing, mostly numerical data in order to sufficiently corroborate its theories (Saunders, Lewis and Thornhill 2009:151). Thus, highly structured quantitative approaches are based on measurements, condition monitoring and analytic tools which enable and assure repeatability of procedures and results (Thomas 2003). Similar to the target of deduction, quantitative methods try to deduce valid and objective results that emerge from the specific to the general. A comparison of characteristics of qualitative and quantitative approaches according to Oakley (1999) is shown in Table 3-1.

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Table 3-1: Qualitative vs. Quantitative paradigms  
Adapted from Oakley (1999)

As highlighted by Berman, Drezner and Krass (2010) energy data lacks applicability in reference to availability and accuracy so that the need for specific investigations in this field becomes clear. The controlled observation of quantitative energy consumption data forms the exploratory realisation of the research requirements as identified within the comprehensive literature review as well as the compensation of the weaknesses of existing models as output of the descriptive research part.

The research by Xi et al. (2013) investigates the impact of processes and process structures to location modelling and by this highlights the importance and negligence of process sequences within scientific investigations. These process characteristics form the analysis body for the integration of energy data and are assumed to be stable in its values and structure. The reference to this objective and numerical data set depicts the quantitative basis of the pursued research, so that the overall research method necessitates a combined approach of quantitative data sets and by this addresses the identified demand for a quantitative optimal model (see section 2.2 [p.11]).

In reference to the pursued research project, the research method can be categorised as a mixed approach. Research Phase I relies on the detailed analysis and explanation of the research environment in order to define the theoretical framework (see Figure 3-4 [p.65]). The first part of RP II deals with the development of research approach specific KPI in reference to process energy consumption in order to generate the fundamental components of the research. This field research serves as justification and verification based on existing scientific

knowledge and by this prepares the development of the conceptual model. The second part of RP II deals with the quantitative process data collection and model validation, which is the basis for the execution of the case study simulations in RP III. This phase deals with the conduction of a case study in order to describe and explain the constitution of potentials for increased efficiency.

Each data collection method is characterised by individual advantages but also contains shortcomings that influence the research execution and therefore need to be dealt with.

Intrinsic weaknesses of quantitative approaches are based on the missing information on contextual factors, the time consuming data collection for long period investigations in order to collect a sufficient amount of data and the inflexible data collection operations due to the employed instruments (Creswell 2009, Thomas 2003, Taylor 2005).

In reference to energy data collection, the weakness of being a time intensive and high data volume approach for data collection has been addressed by the research executions using data loggers for the energy data collection in order to track data and to directly transfer the information to a digital output. Data storage and analysis were executed based on Microsoft Excel in order to minimise calculation times. In this regards, the data collection on energy consumption data as per section 4.2 [p.89] and analysis excluding investigation setup and preparation was operated within five days.

In order to counteract the weaknesses linked to process data collection on material handling process characteristics, the combined method approach was used so that the processing of energy data would help to interpret and explain the results and variations within the investigation outcome. Within pilot data collection quantitative data was monitored and the data loggers and sensors were adapted to the desired data output, so that target specific and sufficient data was tracked in order to balance the inflexibility aspect. As explained in section 6.2 [p.144] quantitative data collection encompassed the total of 121 days with more than 1,252 hours of process data including drive routes, process allocations and break times. As the case study execution was operated on six vehicles in parallel, the data collection was carried out within 30 days of operations. The subsequent data analysis was operated on a designated simulation tool based on Microsoft Excel Visual Basic for Applications in order to reduce the analysis times (see chapter 5

[p.105]). Simulation times ranged between 20 to 30 minutes per case simulation. As the practical applicability of the investigation framework and the developed algorithm formed an important part of the research project, high attention was given to the quantitative data collection on process information within its real application environment.

#### **3.4.4 Research Strategy**

Defining the research strategy involves the clarification of quality and quantity of data, the process of data generation and analysis as well as the procedure for developing and testing the research theory (Buckley, Buckley and Chiang 1976:3). The research strategy can be differentiated among opinion, empirical, archival and analytic approaches according to Table 3-2 which also illustrates the associated research methods that are explained in the following executions.

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Table 3-2: Research strategies  
Adapted from Buckley, Buckley and Chiang (1976)

Empirical studies rely on exploratory procedures by observation or experience where there is direct access to data by whether case, field or laboratory methods. According to Buckley, Buckley and Chiang (1976:4) empirical studies consider 'real world' data in order to prove or disprove research theories, whereas attention needs to be drawn on the integration of whether first or second-hand data in order to ensure data reliability. Due to its exploratory research purpose, the pursued research needs to be based on an empirical approach (see subsection 3.4.1). Related operation approaches in reference to an empirical study are explained below.

Research operations refer to the variety of tools and techniques which are used in order to operate or conduct a research (Kothari 2004:7). Whereas some of the

available approaches can clearly be categorised as applicable to inductive or deductive research, the affiliation to one approach provides no evidence for being of superior or lesser quality. This is attributable to the fact that the importance lies in its contribution to answer the research question and to meet the research target (Saunders, Lewis and Thornhill 2009:141). In addition to the value of target orientation, availability of time and resources influence the choice of an adequate approach. According to Table 3-2, existing alternatives within empirical investigations are Laboratory, Field and Case studies.

Laboratory and field studies are accounted among experimental approaches which are often used in natural science research in order to answer the questions of 'how' and/or 'why' (Yin 2009:8). The purpose of using experimental designs of laboratory and field studies is to research causal links of two or more variables in order to detect interdependencies and changes in outcome that result from alternating one or more of the considered parameters (Hakim 2000). In both approaches, field and laboratory, interdependent variables are controlled and can systematically be manipulated and altered in order to observe and compare the resulting changes in an ex post versus ex ante examination (Saunders, Lewis and Thornhill 2009:142).

In general, experimental designs adhere to the following five steps (Saunders, Lewis and Thornhill 2009:143-144):

- Definition of theoretical hypothesis
- Sample selection from known control groups
- Random allocation of experimental and control group under alternative experimental conditions
- Manipulation of one or more of the referred variables
- Monitoring of a small number of dependent variables
- Control of all variables considered

Laboratory studies rely on a limited number of samples and therefore are highly impacted by sample selection and experiment environment, so that this approach frequently lacks applicability to real world circumstances due to the artificiality of the laboratory (Saunders, Lewis and Thornhill 2009:143). Field studies are often limited to the degree of manipulation as well as the restricted adaptability due to

ethical reasons (Cooper and Schindler 1998:382–383). Experimental approaches often try to overcome their inherent weaknesses by increasing the number of samples, so that complexity and the risk of overrunning budget increase (Hakim 2000).

According to Robson (2002:178) a case study can be defined as ‘a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context’. In accordance with this definition the basic difference from experimental design to case studies can be outlined as the disparity in control from highly controllable in laboratory to less controllable in field to non-controllable in case study approaches. According to Morris and Wood (1991), case studies are particularly practical in order to understand and rely to the research context/environment, so that the on-going development of case study operations has positioned them among the established empirical methods in engineering studies (Flyvbjerg 2006). Case studies are often used in exploratory and/or explanatory studies using single or combined techniques such as interviews, observation or documentary analysis etc., which create the necessity to prove reliability and validity (Saunders, Lewis and Thornhill 2009:146).

Benbasat, Goldstein and Mead (1987) as well as Eisenhardt (1989) call attention to the appropriateness of using case studies especially within the developing phase of a research field, i.e. when there is limited prior knowledge in the specific field (Yin 2009). As there is only a limited amount of literature and scientific work in the field of electric charging station allocation and none specifically on occasional recharging as discussed in section 2.6 [p.33]), case study executions can explicitly explore this area where there is little understanding, so that case studies can provide reliable data, information (Symon and Cassel 2012, Eisenhardt 1989, Yin 2009) and by this, new knowledge in the field of charging station allocation for occasional recharging. The execution of a case study enables in-depth research given that the investigation object is dependent on several impact factors (Verschuren 2003).

According to Yin (2003) a further classification of case studies differentiates between single and multiple cases. Single cases refer to a critical, unique or extreme case where there is a lack of comparison cases. Alternatively, single case



approaches are suitable for typical cases with low deviations or for cases that have rarely been observed and/or analysed before in order to define a reference model/case as guidance or basis for further and broader investigations (Saunders, Lewis and Thornhill 2009:146). Furthermore, the execution of single or fewer cases allows the researcher to focus on detailed in-depth analysis in order to explore the investigated phenomenon (Voss, Tsikriktsis and Frohlich 2002). Multiple cases foster the applicability to more than one case and show a first step to the deduction of generalisations, so that multiple cases are preferable in order to generate a hypothesis and to prove it from the investigated findings while requiring more time for its execution (Yin 2003).

As a starting point for research in the defined field, the pursued research is based on a single case study in order to allow a thorough and detailed analysis of the research environment. Monitoring several different vehicles collects material handling process data as being the quantitative basis for the case study execution. While these vehicles operate within one production facility and are firstly investigated in isolation, in a second step the individual profiles and results are set in relation within a combined investigation. The benefit of this research approach is to investigate the actual state in man-guided material supply processes in a production environment, to gather and analyse typical process information and to test the allocation model towards its robustness. The developed location-allocation model and framework as the basis for the executed simulations serves as a reference model and starting point for further research in this field.

A research strategy inherent weakness of a case study is the basis of theory on cases, so that Eisenhardt (1989) addresses the difficulty of the results to not provide a full understanding of the phenomenon. In contrast, Yin (2009) argues that this can partially be balanced by a comprehensive literature review as well as the reference and model design based on existing knowledge and studies as executed within section 2.7 [p.50] of this research. A further vulnerability of case study research is the undefined amount of data being required in order to provide an in-depth case review. In order to supply a sufficient amount of data, this research consists of a total of seven investigation objects in line with the seven-samples rule by Eisenhardt (1989), being represented by each vehicle investigated over a minimum of 14 days as well as a combined fleet investigation. The

problem of data saturation especially in case study investigations can generally be seen as achieved when any further data set does not contribute to increased information (Glaser and Strauss 1967, Bogdan and Biklen 2007). The collection of a total of 121 days of process data showed minimal recharge energy shifts as bottle neck cases with an average deviation of 17% from the average case as case study extreme. Standard deviation from the average case was about 8% with 84% of all cases being within this range.

### **3.4.5 Case research execution**

As with all research methodologies, case research is characterised by its individual challenges and requirements that need to be addressed within the process of research execution. The major challenges within case study execution are that of obtaining access to organisations, as well as the attainment of the required data quality within the case study environment (Easterby-Smith, Thorpe and Lowe 2002).

#### **3.4.5.1 Case study challenges**

Given that occasional recharging and electric charging station allocation within industrial application have this far been neglected within scientific investigations and constitute a relatively new field of research, researchers are required to collect empirical data in order to obtain access and become closer to the object of study. On the other hand access to organisations and data collection in real fields can decelerate the research performance (Easterby-Smith, Thorpe and Lowe 2002). The author's previous work experience enabled access to assembly line manufacturers and material handling producers as a first contact, whereas due to the sensitive nature of the data needed, most interest in collaborative process and energy data collection emerged from the material handling producers. Data collection was executed in agreement with the works council, which represents the interests of workers (Oberfichtner 2016), in order to abide by the ethical principles and the set timeline (see subsection 3.4.5.2, section 0).

As the target of a case study execution involves the collection of empirical field data, this approach requires a more rigorous procedure and in-depth analysis in order to generate the required quality, reliability and validity of data and results. Therefore, data collection was operated on generally available data loggers with

high data granularity and a structured collection approach that was elaborated and assessed in collaboration with organisation experts (see also section 4.3 [p.100]). As the collected process data constitutes sensitive information, a signed non-disclosure agreement was sent to the organisation prior to data collection in order to confirm that no information and data will be disclosed to third parties and the data is handled with complete anonymity (see Appendix E). Furthermore, the researcher, as well as the organisational decision maker did not participate in or interact with human operators during operations in order to ensure regular operations.

#### 3.4.5.2 Sample selection

Throughout the theoretical investigations on location-allocation, charging infrastructure modelling, energy monitoring and the combination of these aspects within a comprehensive framework and model for occasional charging station determination, it was seen as necessary to put the methodology under a more thorough examination by applying it to a specific case research environment. To ensure the comparability of the case study results as being a valuable and reliable source of information, the case study environments importance to the development of knowledge had to be carefully considered. For case selection, it was important that the case study presents a sample on material handling within a stable production environment, so that the selection criteria for potential case study environments according to Table 3-3 were applied. The criteria for case qualification were identified based on definitions of line manufacturing and its related material supply processes of section 2.3 [p.15] (Chow 1990, Boysen, Fliedner and Scholl 2007) and in line with the criteria defined by Mueller, Krones and Hopf (2013) and Mueller et al. (2013).

#	Criteria	Application
1	Main (production) processes are clearly defined	Production processes are operated on assembly lines, so that production targets on a stable production at high efficiency.
2	Several sub processes supply a main process	Several feed-in locations are allocated along each assembly

		line, showing the complexity of material supply processes.
<b>3</b>	MH processes are investigated based on individual electric vehicles	Components are supplied by electric forklift trucks, with the possibility to be monitored separately.
<b>4</b>	Operations are executed on a fleet, i.e. min three, vehicles	To show model applicability from single to any number of vehicles, facilities with more than five vehicles for investigations on different vehicle combinations were considered.
<b>5</b>	EV are determined by defined functions and tasks	Industrial trucks are dedicated to specific tasks and assembly lines within the defined production warehouse.
<b>6</b>	Minimum operation of one shift per day	Processes with a minimum of 8 working hours per day were monitored to identify the potential of occasional charging.

Table 3-3: Case study qualification criteria

Source: Author

As the target data to be collected presents detailed information on production processes as well as facilities and therefore contains confident company information, it was quite difficult to find appropriate case study partners in respect to the above mentioned qualification criteria. Furthermore, the legal and organisational preparation of the data collection, the coordination with the works council and the installation of data loggers and markers constituted time consuming investigation components, so that the number of case studies was limited. To get in touch with possible case study partners, these were initially contacted by phone, so that the research project could be explained and questions answered in more detail. Afterwards, the contact persons were emailed to provide written information to them and other members of the company.

The case study preparations involved the participation of the case study partner within facility evaluation and disposition, identification of vehicles, obtaining of data collection authorisation, the integration of process monitoring preparation

within regular operation and support for regular data transmission to the researcher within the pilot and final case study phase.

Due to the above factors in respect to time and coordination efforts for and with industrial producers as well as the complexity of data and simulation processing, the research executions focus on the comprehensive analysis of one case study environment with a total of six vehicles to be examined within an assembly line environment by individual and combined case analyses. The production site as well as the manufacturer characteristics corresponded to the defined criteria according to Table 3-3 and in addition to this, the case study partner as per executions of section 6 [p.144] showed a high interest on the information on their production processes, equipment use rates, energy consumption values as well as optimal charging station allocation and therefore provided valuable support, information and company management time throughout the investigation operations.

#### 3.4.5.3 Case study ethics

In order to ensure the ethical conduct of research, clear rules for investigation execution were defined in collaboration with the works council prior to any data collection. These included the rights of participants, the target and use of collected data and generated results, as well as the level of data security and anonymization.

In line with this, participating drivers were informed on the contents as well as targets of the data collection and the research project, their rights to withdraw from participation before and during data collection of the pilot and final case study as well as the use of the collected data and the deletion of the data after project target result generation (see Appendix E).

Furthermore all data was agreed to be anonymised in respect to the truck number, driver as well as the time, day and shift of data recording in order to prevent data to be traced back to individual drivers and their individual behaviours. Besides of ethical principles, anonymization was expected to contribute to decreased sabotage of the tracked data as drivers were encouraged to act according to their normal working behaviour in order to increase data quality.

#### 3.4.5.4 Case data collection process

As explained in the previous sections on the research environment, the generation of research specific KPI of RP II is subdivided into energy and process data collection, meaning that within the data collection this differentiation needed to be maintained.

In order to generate the required energy consumption data, industrial trucks being used within the investigated production warehouses for process data collection needed to be equipped with sensors for voltage and current data measuring. Standardised material handling functions were repeatedly executed on these trucks as per the descriptions on energy data collection of section 4.2 [p.89] in order to generate a standard for energy consumption value generation. The Standardised Energy Consuming Activity (SECA) approach produces simple-to-generate data for different material handling equipment and simple-to-use data with general applicability to processes on similar handling equipment (see subsection 4.2.1 [p.90]). The generated energy consumption data, i.e. the measured information is mathematically checked for its validity after a number of test runs as per explanations of subsection 4.2.3 [p.94] in order to serve as a pilot study to test the research instrument (Baker 1994).

For quantitative energy consumption data collection, state-of-the-art industrial trucks of average size in reference to vehicle mass, engine performance and lifting capacity were identified in order to serve as a general applicable reference model. Data collection was executed on the model Linde E16 as representative sample. The technical data can be taken from the data sheet in Appendix B. The considered counterweight trucks have a lifting capacity of 1.6tons to 2.0tons. The net mass of the truck is given as 2.4tons. KPI generation according to the SECA approach can be executed on any industrial truck, i.e. electrical material handling equipment, so that the replicability of this approach is assured.

After test monitoring of process data according to the explanations of subsection 4.2.2 [p.92] for five consecutive days, data loggers were permanently installed on a minimum of five industrial trucks for a duration of 14 days. This procedure ensured the generation of a reliable source of data for data analysis of minimum seven data sets as per minimum case number requirement by Eisenhardt (1989). The pilot installation of data loggers showed gaps within the recorded data due

to system calibration and insufficient marker installation. The maximum distance from marker to marker was identified to not exceed 50m, so that additional markers needed to be installed.

By this data sampling procedure each data set of an individual truck is treated as an individual sub-case, as trucks have their individual driving and process patterns due to individual production tasks. Single trucks are dedicated by production organisation to specific production related functions and components. Comprehensive fleet simulations complete the set of investigations, whilst individual truck related results are compared to fleet investigations in order to test the outcome reliability.

The described pilot studies were executed in order to base the data collection and formatting on comprehensible instructions, to ensure sufficient data collection procedures as well as reliability and validity of research outcomes and to determine correct statistical and analytical processes (Simon 2011). Yin (2009) defines convenience, accessibility, as well as geographic proximity as main selection criteria whereas for the pursued research approach, pilot investigations were executed in the environment of final data collection in order to integrate handling equipment operators into the case study development and to avoid their resistance to the investigations. The pilot case study generated a valuable basis of information in reference to data structures and quality, so that data generation and formatting as well as the development of the simulation tool were improved. From a broader set of collected information such as vehicle orientation, z-coordinate, distance to marker, pressure sensor values, etc., simulation relevant information was extracted in order to decrease the volume of data to be handled and stored (see subsection 4.3.2 [p.101]).

#### **3.4.6 Research Content**

The previously described Research Phases I to III are of consecutive character, so that RP I and RP II provide the quantitative input for the executions of RP III. Therefore the research project execution follows the consecutive approach as per the following explanations in reference to the research phase contents.

**Research Phase I – Literature Review**

The executions of a comprehensive literature review in fulfilment of RP I form the theoretic and scientific foundation of the pursued research approach. The literature review on the research environment highlighted the importance of the defined key performance indicators in the development of the dedicated framework. In reference to existing location-allocation modelling, the literature review showed the existence of electric charging station allocation models, but emphasised the lack of applicability to the specific research environment, as well as the negligence of occasional recharging. As such, a dedicated model needed to be developed.

**Research Phase II – Research environment investigation**

The target of RP II is to exercise field investigations in order to define and format target specific KPI in reference to the defined fundamentals. The development of research environment specific numbers in reference to energy consumption, energy supply and process characteristics are an essential parts of this research phase. Furthermore, RP II collects quantitative process numbers as fixed, structural input for location-allocation modelling and as basic information for the executed simulations of RP III.

**Research Phase III – Mathematical modelling and simulating**

Research Phase III deals with the mathematical modelling of a subject specific location-allocation model in order to most realistically simulate process potentials for occasional recharging and to subsequently calculate the impact to efficient and sustainable system improvement. The calculations on optimised system allocation highlight the meaning of and need for process specific investigations, proving that the generation of a generally applicable framework is a key feature within this field of research. The framework design allows investigations in related research environments and to calculate improvement potentials fostering further research in the field of occasional recharging.



### 3.5 Analytical Modelling

In order to foster detailed investigations on real systems, analytical models can be used as substitutes which simulate system behaviours. Models can be differentiated between physical and mathematical models. Mathematical models refer to the representation of physical models based on the development of logical relationships, so that system behaviour can be analysed by manipulating and changing input variables (Law 2007).

A further distinction differentiates mathematical models into analytical solutions and simulations. Simple models, which are based on logical, quantitative descriptions, refer to analytical solutions. These models can easily be manipulated in order to investigate system changes. More complex analytical solutions, e.g. based on linear programming, are executed by simulations in order to describe and investigate the researched system (Law 2007).

The comprehensive literature review on the research environment and its components as well as on electric charging station location modelling highlighted the complexity of the investigation object, so that the representation in an analytical simulation model is seen as an inevitable step in order to define and analyse the impact from technology implementation to the material handling system and its design. Schmidt and Taylor (1970) defined a system as ‘a collection of entities which act and interact together toward the accomplishment of some logical end’. Using this focus as a springboard, a system can be defined to be a production facility with its machines, components and processes to be the considered entities (Schmidt and Taylor 1970; Law 2007).

In line with the descriptions of Evans and Olson (2002:12f), a structured simulation process comprises the following five steps:

S1: Development of a conceptual system model

S2: Definition of a simulation model and data collection

S3: Model verification and validation

S4: Simulation

S5: Experiment execution and result analysis

Figure 3-5 displays the structure of the analytical model being employed for the research execution. The initial step prepares the research model development and simulation execution. It includes the target specific problem definition and determines all input variables and factors as well as output measures in reference to the Lean and Green target definition of section 2.2 (S1). This step is the basis for the mathematical model programming (S2). Verification and validation are essential steps of the scientific process realisation in order to test the developed model (S3). Data collection addresses the mult method approach in reference to the collection of quantitative case study information. In step S4 the collected data and information from S1 to S3 is used for simulations in order to generate system results for final analyses (S5).

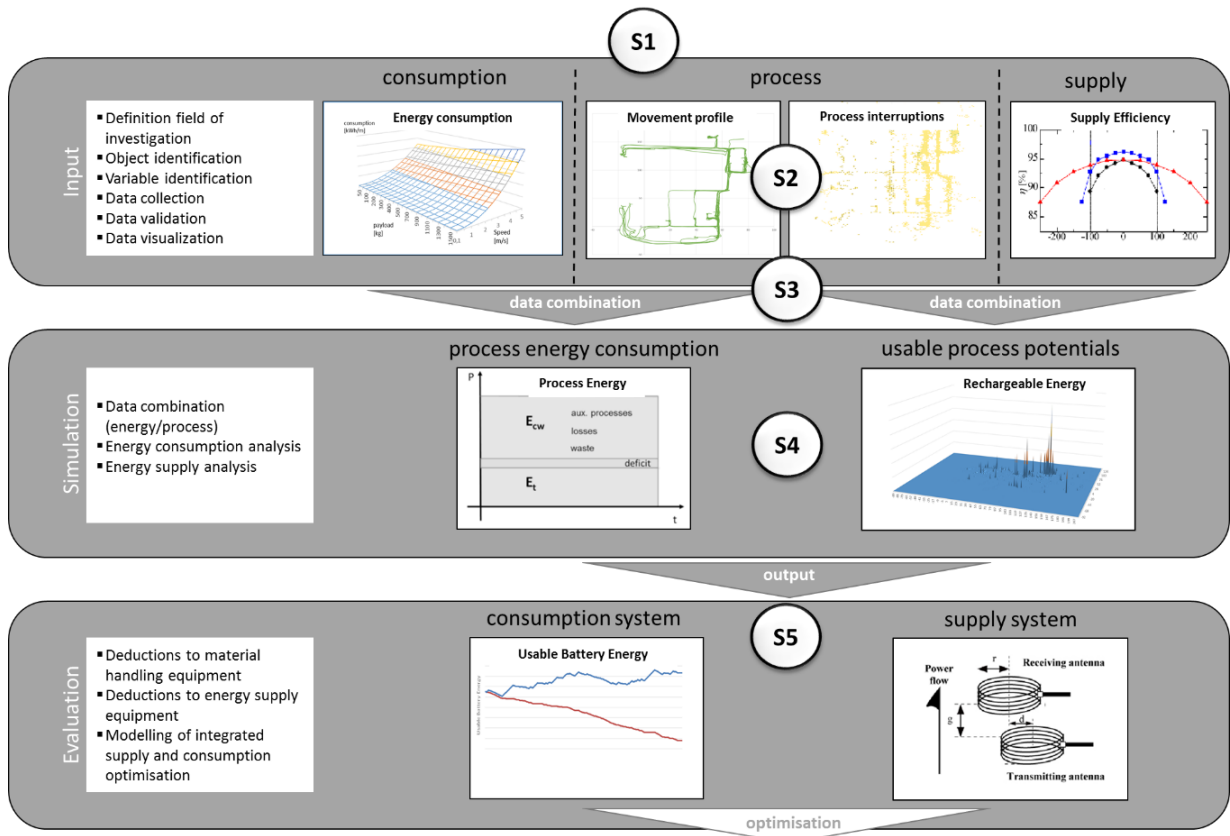


Figure 3-5: Analytical model  
Source: Author

The described simulation modelling enables controlled system manipulations with no exposure to the violation of ethical principles. Simulation costs for model development and execution are generally lower than physical system realisation

for testing. Time sequences can be de- or accelerated in reference to the research target and risk is minimised as manipulations or failures do not negatively impact the real system application (Evans and Olson 2002).

In order to simulate system properties, behaviours and potentials, the developed model needs to correctly define the structure and relations of input and output factors. Therefore, these variables need to be determined, defined and formatted in reference to the research target and subsequently be combined by mathematical functions.

### 3.5.1 Evaluation Framework

In order to evaluate the potential of occasional recharging, simulations need to generate optimal charging station allocations based on a dedicated location-allocation model. The research compares charging station integration in locations of maximal break time occurrence under the assumption of a fixed covering distance and the impact of the covering distance definition as a function in reference to the positive contribution of break times to the system energy balance. The generated potentials are then evaluated based on their contribution for increased resource saving in respect to battery capacity, cost and overall CO<sub>2</sub> emissions as benchmark for increased sustainability.

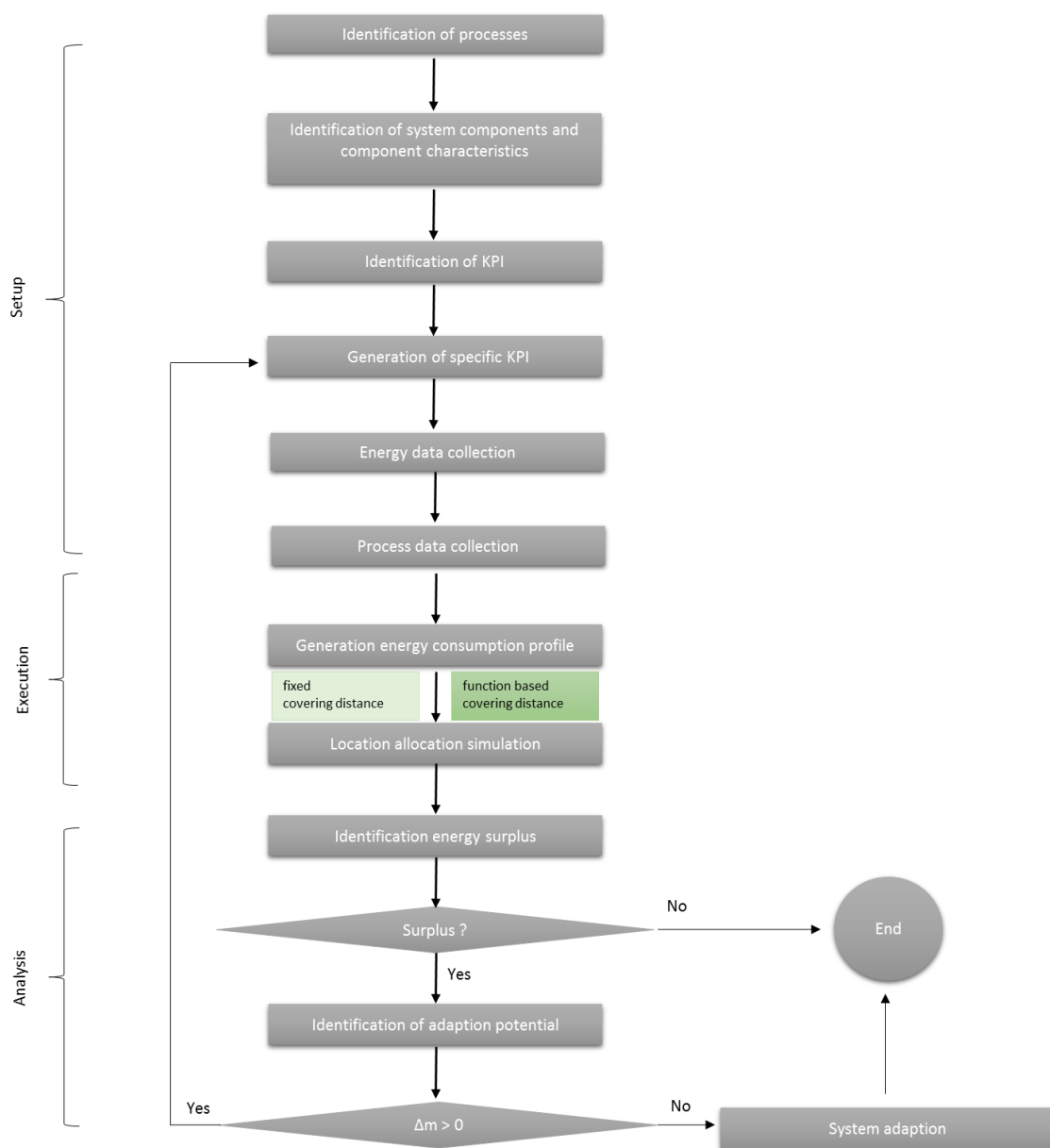


Figure 3-6: Evaluation framework  
Source: Author

The research investigates how changes of the covering distance definition impacts the process potential and charging station allocation in order to identify the preferable location-allocation model. Therefore, the dedicated framework as per Figure 3-6 for charging station allocation for occasional recharging was developed. The results of changed covering distances will be compared by analysing the potential for the described resource savings. Used input variables as well as their mathematical combination in reference to the developed framework are described in section 5.3 [p.126].

### **3.5.2 Spread sheet Simulation**

In order to simulate and analyse the research subject, an Excel based tool has been developed in order to solve the mathematical problem formulation in reference to linear programming. The arrangement of equations and mathematical formulations, as per explanations of section 5.2 [p.106], facilitates the data analysis. This spread sheet simulation was chosen in accordance with software availability, accessibility and applicability to the investigation process.

Due to the research project realisation of the author in collaboration with industrial partners, Microsoft Excel was identified to be of widespread industrial application so that information and data sharing was facilitated. The use of any other software than Microsoft Excel VBA would have resulted in the necessity of software procurement by the researcher as well as possible end users if simulations are targeted to be executed outside the research project. This alternative would most likely increase the need for additional training of end users.

The application of other tools such as MATLAB Simulink or similar would have required further training of the researcher as well as further coordination efforts in respect to joint information and result sharing. Furthermore, the use of off-the shelf software was further discounted as it would in any case, have necessitated an adaption of existing included simulation tools to realise the necessary optimisation calculation structure and procedure identified.

### 3.6 Validation and Reliability

Defining and designing measuring tools and equipment for data collection, validity and reliability need to be investigated in order to ensure and generate the required degree of quality and credibility of the research findings (Saunders, Lewis and Thornhill 2009:156-159).

Rubin and Babbie (2011) define validity as the extent to which empirical data collection fulfils the function of target oriented generation of numbers according to the original intention, while Cooper and Schindler (1998:166) add the importance of practicality of the measuring process. Validity can be differentiated between internal and external validity. Internal validity deals with the target fulfilment of data collection, i.e. the degree to which tools and instruments record the data as per research indication. External validity focuses on the inherent potential of the research to allow generalisations, i.e. whether research findings are also applicable to other research settings (Cooper and Schindler 1998:166). Case studies mostly neglect the attempt of generalising results as the target is 'to test the robustness of conclusions and theories by exposing them to other research settings in follow-up studies' (Saunders, Lewis and Thornhill 2009:158), so that for the pursued research external validity is not a key target.

Reliability within data collection methods and research procedures is defined and characterised by a high degree of consistency, meaning that random repetition of similar observations will lead to similar results and outcome (Bryman and Bell 2007). Figure 3-7 shows the relationship of validity and reliability in order to back up the following explanations on how these are interlinked and interacting.

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The bottom left image shows the hits to be spread in different areas of the target, so that the results are not concentrated on a specific area (reliability) and do not hit the target area in the centre (validity). The resulting research design and outcomes do not correlate to a structured research approach and thus lack credibility.

The top-left image shows results that are reliable but invalid, meaning that the hits are located in a narrow area but do not match the target. This research is characterised by consistency, i.e. reliability, but does not lead to and support the target outcome of the research approach. The results of bottom-right research refer to the enlarged research area but lack consistency. It is a mixture of the preceding alternatives which does not produce the desired outcome. Correspondingly, validity can be seen as insufficient. The top right illustration shows a combination of validity and reliability, so that the specified research target is correctly addressed and the collected data is consistent in its quality.

The above executions illustrate that research results can be reliable despite their invalidity, but there is no validity of results that are unreliable. By this, Cooper and Schindler (1998:171) define reliability as an essential contributor to validity whilst it cannot be seen as sufficient proof of validity.

In order to prove reliability of the pursued research project, the simulation design is based on existing mathematical problem solutions, as well as location-allocation models in specific adaption to the research questions. Furthermore, subsection 5.2.3 [p.115] compares manual and tool-simulated results in order to ensure reliability.

The definition of the research environment including system KPI of section 2.4 and the research target definition of section 3.2 determines the research subject as well as the pursued outcome of research. Various discussions with collaborating company representatives as well as the drafted plausibility and reliability check of section 5.4 [p.140] vouch for the research model's validity. The scientific approach for the systematic achievement of validity and reliability is presented below.

### 3.7 Triangulation

The term triangulation refers to the utilization and combination of 'two or more independent sources of data or data collection methods' (Saunders, Lewis and Thornhill 2009:154) in order to strategically investigate reliability and validity of research (Denzin 2009). The benefit of combining single methods or sources of data which test the same findings, whereas every method or source itself must be proven to be reliable and valid, is to decrease the overall influence of disadvantageous aspects in order to compensate potential deviations and inaccuracies (Babbie 2010). In contrast to this wording, triangulation requires only a minimum of two options and has no maximum limit so that more than three methods can be used (Rubin and Babbie 2011:298).

According to the model of Saunders, Lewis and Thornhill (2009:152) and as per Figure 3-8 single methods can be used whether isolated in a mono method approach or as a combination as multiple method. While applying multiple methods of one research approach only, multi method studies refer to whether using qualitative or quantitative methods, whereas the combination of qualitative and quantitative methods is associated to mixed methods.

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Figure 3-8: Research choices

Adapted from Saunders, Lewis and Thornhill (2009)

Due to the complex structure of the investigated research environment that requires several investigation steps and perspectives including the execution of a comprehensive literature review and quantitative data collection being combined within the analysis part into a case study simulation, the triangulation approach has to address these aspects as multi method operation that proves the reliability of all executed investigation steps. In order to increase the credibility and integrity



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of the research, results as well as data input, processing and output were presented and discussed with research environment experts in order to verify the results. This additional form of verification and plausibility testing as applied to the research execution is described by Saunders, Lewis and Thornhill (2009:298).

### **3.8 Chapter Summary**

This chapter described the chosen research design and methodology used in order to answer the defined research questions. The combined research approach uses inductive and deductive elements being based on a multi method research of quantitative data in order to enable simulation operations. The evaluation framework (see Figure 3-6 [p.83]) shows the analytical model which is executed by the case study investigations. The first part of the realisation of the triangulation model is based on the executed literature research which identified the research environment, important KPI, the gap within research in reference to location-allocation modelling and defined the process of data collection. As a second part, data collection contains the stepwise generation of reliable and valid research findings as explained in the following chapter 4 and forms the basis for the development and design of a subject specific location-allocation model for the potential analysis and evaluation as described in chapter 5 [p.105].

# CHAPTER 4

## DATA COLLECTION

### 4.1 Introduction

Data collection is a fundamental element of any research project since the success and acceptance of the scientific results depend on credible and reliable data. The decision to employ the applied research method is attributable to an array of factors such as data access, availability of data collection tools, research aims and objectives as well as method inherent pros and cons. This means the one best method for data collection is inexistent (O'Leary 2004).

As explained in subsection 3.4.3 [p.65], the pursued research method adheres to a multi method approach that combines quantitative data sources which is outlined and justified by the presented explanations of the following chapter. Each part of data collection is examined based on its individual reliability and validity in line with the previous explanations on triangulation of section 0 [p.87]. Quantitative energy data is collected in order to thematically analyse the fundamentals of the research environment according to research question Q3. The material handling process data collection integrates the energy consumption and provision data into a case study simulation (Q4) with the target to answer Q5 and Q6 of Research Phase III. The collected and generated data is based on the prevalent SI unit system which is complemented by the established unit of energy given in kWh (Mueller et al. 2013).

### 4.2 Energy Data Collection

Quantitative data collection focuses on the numerical collection and analysis of a research subject in order to clarify the questions of 'what' and 'how much' (Pinsonneault and Kraemer 1993). In doing so, the quantitative approach involves the objective and numerical collection of data in order to visualise and analyse the findings displayed in graphs, tables, charts etc. being generated by statistical methods.

The target of high quality energy data and its collection is to harvest understanding about the nature and character of impact factors in its research environment context, so that theoretical knowledge and practical experience become combined (Myers 2013). The approach involves a small quantity of high quality data in order to holistically describe complex research phenomena in reference to data reliability and validity.

The executed research approach focuses on the generation and analysis of energy consumption data based on an energy monitoring approach in order to generate the fundamental data for subsequent case study investigations. Data collection and analysis were prepared and operated in February 2015.

Aside from the advantages of increased flexibility and adaptability to the specific research target, Greener (2008) elucidates the weakness of low volume data investigations to be highly influenced by the researcher's choice of data collection model and environment. In order to reduce the impact on data quality, the approach taken focuses on energy monitoring based on the data choice by Chow (1990), Mueller et al. (2013) and Mueller, Krones and Hopf (2013) according to the explanations of section 2.4 [p.26] in combination with mathematical data inspections in order to ensure data validity.

#### **4.2.1 Energy Consumption Data**

According to the executed literature review, existing research in the field of investigation lacks adequate energy figures in order to explore the research target by executing subject specific case study simulations. Consequently, energy data in reference to the defined performance indicators needs to be generated to enable the development of an occasional charging station allocation model.

Energy Monitoring, otherwise known as Electrical Monitoring, deals with the systematic collection, measuring, presentation and analysis of data of electric machines with reference to its performance and energy consumption (Mueller et al. 2013:622). An important issue of energy monitoring is to determine process parameters which influence individual processes and, by this, to identify generalizable functions in order to make a process-based energy monitoring approach applicable to similar, comparable functions. Therefore, energy monitoring has to focus on processes broken down to standardised handling steps and functions that also

occur in other processes or redundant in the same process in order to make it generally applicable. The target is to define Standardised Energy Consuming Activities (SECA) that fulfil congruent and/or redundant functions, are determinable and easy to identify in reference to their appearance within investigated processes. A SECA therefore has to be clearly defined and as specific so that it can also be defined as 'not reasonable divisible' in order to determine its value. A SECA in material handling of logistic hubs can be defined as the task of forwarding a certain weight over a certain distance by measuring the required energy. The distance can be set to one meter, as average transport distances are generally given on a metric basis. Breaking it down to a smaller unit may not provide any further benefit to energy calculations. Due to the generation process of SECA within this application being based on average values including acceleration, constant movement and deceleration, the SECA values can also be adapted to smaller fractions by mathematical calculation if required, whereas for the executed research project the basis of SECA on full metres was evaluated to be sufficient.

The fragmentation of material handling processes to smallest material handling functions allows the subsequent defragmentation of material processing into a comprehensive energy consumption profile based on empirical consumption figures which includes the standard deviation for start-up processes and different process encroachments. The defragmentation of processes by using SECA allows a flexible adaption to fast changing processes what enables the desired flexibility for process energy calculations and simulations.

Process and routing optimisations are central aspects of organisational parts of energy monitoring. He et al. (2012) introduced the combination of single process steps of a manufacturing supply chain and its inherent energy consumption in reference to a highly standardised production line. Energy consumption of different operating modes are analysed in order to result in the most economic compromise of energy consumption and process velocity. This approach corresponds with Mueller et al. (2013) and the described approach of introducing SECA. Existing approaches form an initial step for detailed energy analysis, but still lack the process-required particularity in energy monitoring execution. Material handling process energy monitoring is based on and conducted according to the following scheme by segmenting handling activities into single redundant SECA (see Figure

4-1); its defragmentation into a periodic load profile based on a case study simulation enables a detailed process analysis and evaluation.

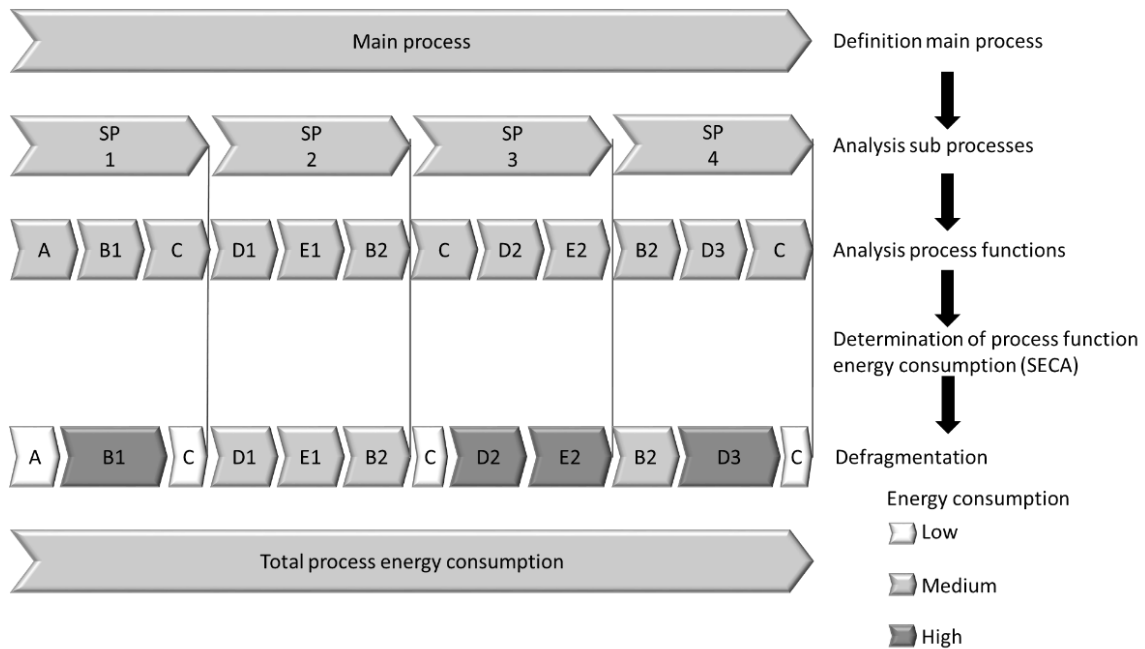


Figure 4-1: Standardised Energy Consumption Activity Generation  
Source: Author

#### 4.2.2 Procedure of Energy Data Collection

In order to generate energy consumption data based on the SECA approach, industrial trucks of the type Linde E16 (see Appendix B) were equipped with the data logger ‘Arduino’. Two shields that were connected to the micro controller were used for a) current and voltage measuring and b) data storage. The data logger records the development of current and voltage five times per second in order to precisely store and display the gradients while executing the developed experiment setup for SECA generation.

The systematic and structured generation of SECA uses a standardised experimental setup (see Figure 4-2) which represents the execution of material handling functions. The granularity of executed functions is based on the smallest unit of function, so that the defragmentation in reference to Figure 4-1 can be executed by adding up individual SECA functions. The repeated execution of the experiments and referred data monitoring demonstrates the comparability and reproducibility of results.

The experiment setup includes the performance of material handling functions such as planar and vertical movement, i.e. driving and lifting actions of the MH equipment according to Figure 4-2 -a and -b.

The planar movement experiment consists of subsequent forward and backward driving of ten metres each, with the result that the functions of accelerating and throttling are executed twice for each data recording. The consumed energy is recorded and broken down to the average energy consumption per driven meter in [kWh / m], so that SECA includes all function immanent process characteristics.

SECA values for lifting are determined by the execution of a) free lift over 0.1m, b) 1.1m stacking and, c) 2.1m stacking. For the experiment execution, the SECA for lifting is defined as 0.1m of vertical movement, so that the measured energy consumption is diminished to this vertical SECA distance (see Figure 4-2 -b).

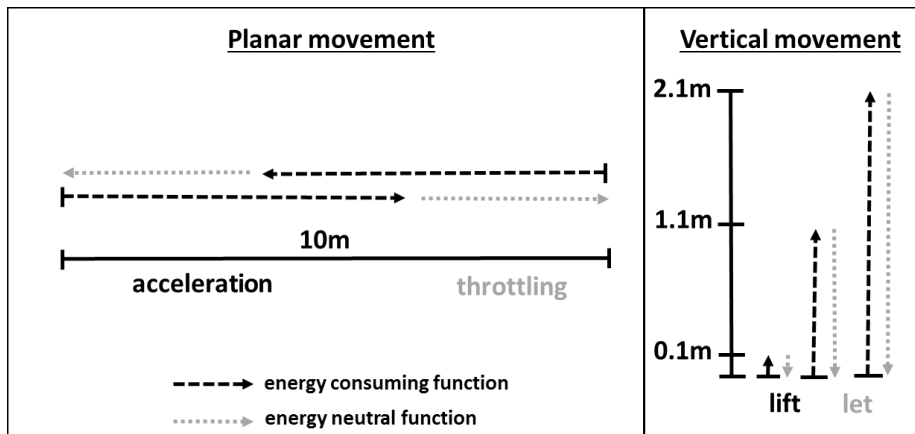


Figure 4-2: SECA experiment setup (planar movement -a; vertical movement -b)

Source: Author

The values of energy consumption for planar movement  $E_D$  are referred to the transported payload over a distance of one meter which includes the vehicle mass (incl. driver) plus the weight of transported cargo. Energy consumption for lifting  $E_L$  is related to the weight of goods in reference to the minimal vertical distance for free lift of 0.1m. In reference to the determination of SECA values ( $W_E$ ), equation (30) determines the total working energy consumption per executed measuring run which is subject to functional fragmentation to consumed energy per meter driven for planar handling and to consumed energy per 0,1m lifted for vertical movements:

$$W_E = \int_{t_0}^{t_1} u(t) * i(t) * \Delta t \quad (30)$$

whereas

u = voltage

i = current

$\Delta t$  = time difference needed to overcome the SECA distance

The characteristics of current and voltage values over time in [s] of planar movement with additional payload of 450 kg are depicted in Figure 4-3. The required energy being necessary to execute the function of planar handling is calculated based on equation (30) and numbered in the following section in Table 4-2 [p.97].

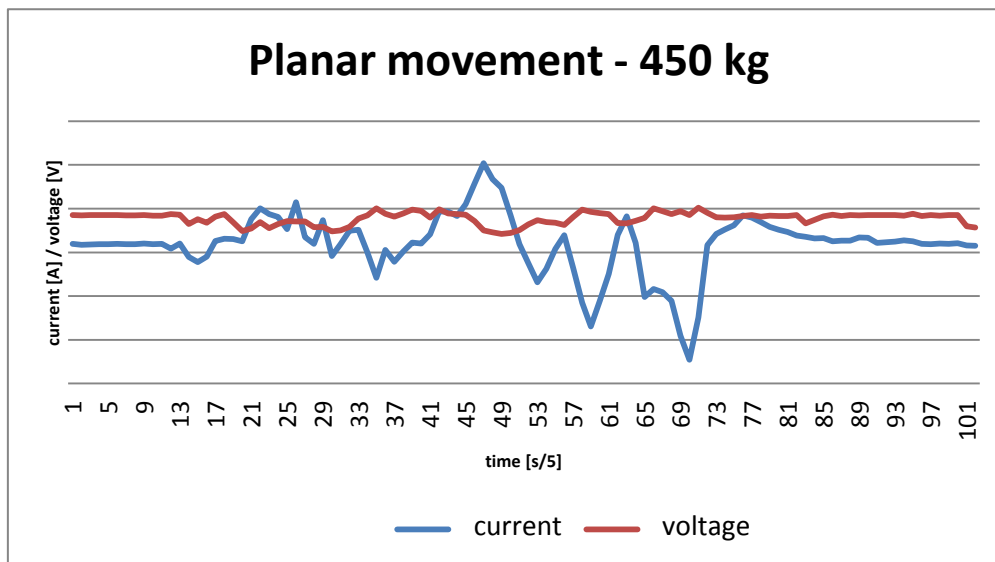


Figure 4-3: Voltage and current values for planar movement - 450 kg  
Source: Author

In order to integrate alternating energy consumption due to forwarding of heterogeneous cargo, the experiment setup needs to be executed repeatedly while handling different cargo weights. This approach is integrated and illustrated within the following explanations on energy data validation.

### 4.2.3 Energy Data Validation

The validation of the collected energy data is based on the reference to the quality criteria of objectivity, validity and reliability in line with the explanations of Saunders, Lewis and Thornhill (2009).

Objectivity refers to the independence of the researcher from any bias towards the resulting values of the research subject in order to ensure the reliability and accuracy of results. Due to the design of data collection being based on statistical data recording, as well as the reference of target data and data content to existing scientific research approaches, a high degree of objectivity is achieved. The reference to existing scientific approaches such as Mueller et al. (2013), Mueller, Krones and Hopf (2013) and Chow (1990) developed the target performance indicators for data collection as per Figure 2-6 [p.28] in order to ensure the validity of results.

Reliability of data refers to the reproducibility of results including data correctness and the absence of random or systematic faults. As such, the collected energy data on planar and vertical movement is mathematically reviewed towards its precision and reliability.

#### Energy data for planar handling

Measured data of individual experiment runs was collected, and average values over all operated runs were defined as basic energy consumption values according to the approach of SECA as shown in Table 4-1.

<b>payload</b>	<b><math>E_D</math></b>
<b>[kg]</b>	<b>[kWh/m]</b>
<b>50</b>	0.001063
<b>75</b>	0.001102
<b>100</b>	0.001157
<b>150</b>	0.001234
<b>900</b>	0.001740
<b>1000</b>	0.001770
<b>1200</b>	0.001804
<b>1400</b>	0.001861

Table 4-1: Exemplary energy data for planar handling

Source: Author

Mathematical verification of the generated data refers to the calculation of process energy for planar handling ( $E_D = E_{cw}$ ) according to Figure 4-4 which contains all integral parts such as target energy ( $E_t$ ) as well as friction ( $E_{fr}$ ), losses, waste and auxiliary energy ( $E_{aux}$ ). The avoidance of a positive or negative deficit refers to the provision of constant availability of material handling equipment with respect to increased efficiency.



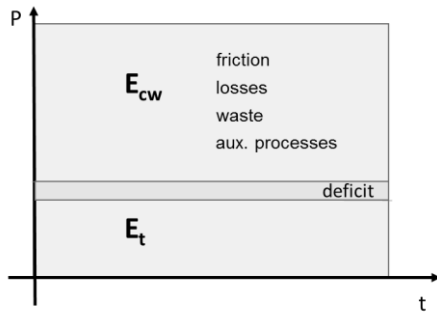


Figure 4-4: Components of process function energy

Source: Author

The basic formula for calculating process energy in planar movement refers to the integration of required kinetic energy and friction losses. Auxiliary energy includes energy input for system provision, transmission efficiency losses, material handling equipment air resistance which are considered within the SECA investigation as the difference in energy consumption from measured to calculated figures, meaning that the investigations on energy consumption data is based on the below equations:

$$E_D = E_{kin} + E_{fr} + E_{aux} \quad (31)$$

$$E_{kin} = \frac{m}{2} \cdot v^2 \quad (32)$$

$$E_{fr} = F_R \cdot s \quad (33)$$

$$F_R = c_r \cdot F_N \quad (34)$$

where

$m$  = total mass handled (incl. industrial truck, battery, driver, cargo etc.)

$v$  = average velocity

$c_r$  = roll resistance coefficient

$F_N$  = axial force

$s$  = driving distance

For the review of measured data, the mass of material handling equipment including the driver is assumed to be constant, whilst the vehicle payload is changed in accordance to the SECA approach by altering the weight of carried cargo. Table 4-2 shows results for calculated and measured energy consumption,

whereas 'E<sub>D</sub> calc' shows the calculated values according to the equations (31) to (34). 'E<sub>D</sub> meas' shows the measured and generated data which includes auxiliary energy (E<sub>aux</sub>) and losses as per SECA approach in reference to Table 4-1. The values of E<sub>aux</sub> present additional losses such as friction, power transfer losses of charging and uncharging, storage losses and auxiliary functions for vehicle system provision that were not considered within the mathematical energy consumption calculations and by this represent the difference from 'E<sub>D</sub> meas' to 'E<sub>D</sub> calc', so that

$$\text{'E}_D \text{ meas' - 'E}_D \text{ calc' = E}_{aux}.$$

additional pay-load [kg]	E <sub>kin</sub> [Nm]	E <sub>fr</sub> [Nm]	E <sub>D</sub> calc [kWh]	E <sub>D</sub> meas [kWh]	E <sub>aux</sub> [kWh]
50	3067.13	466.98	0.000982	0.001063	0.000081
75	3091.24	470.65	0.000989	0.001102	0.000113
100	3115.35	474.33	0.000997	0.001157	0.000160
150	3163.58	481.67	0.001013	0.001234	0.000221
200	3211.81	489.01	0.001028	0.001259	0.000231
250	3260.03	496.35	0.001043	0.001261	0.000218
300	3308.26	503.70	0.001059	0.001495	0.000436
350	3356.48	511.04	0.001074	0.001426	0.000352
400	3404.71	518.38	0.001090	0.001497	0.000407
450	3452.93	525.72	0.001105	0.001514	0.000409
500	3501.16	533.07	0.001121	0.001646	0.000525
600	3597.61	547.75	0.001151	0.001646	0.000495
700	3694.06	562.44	0.001182	0.001687	0.000505
800	3790.51	577.12	0.001213	0.001772	0.000559
900	3886.96	591.81	0.001244	0.001740	0.000496
1000	3983.41	606.49	0.001275	0.001770	0.000495
1200	4176.31	635.86	0.001337	0.001804	0.000467
1400	4369.21	665.23	0.001398	0.001861	0.000463

Table 4-2: Energy data validation planar movement at average speed of 1.38 m/s

Source: Author

The comparison of calculated and measured values shows corresponding values with a difference in values from 'E<sub>D</sub> meas' to 'E<sub>D</sub> calc' that are evaluated to consist of auxiliary functions (see Figure 4-4 [p.96]) with a relatively small energy consumption (E<sub>aux</sub>). The difference in both values indicates a linear increase of auxiliary energy which can be explicated in reference to factors such as friction and mass inertia.

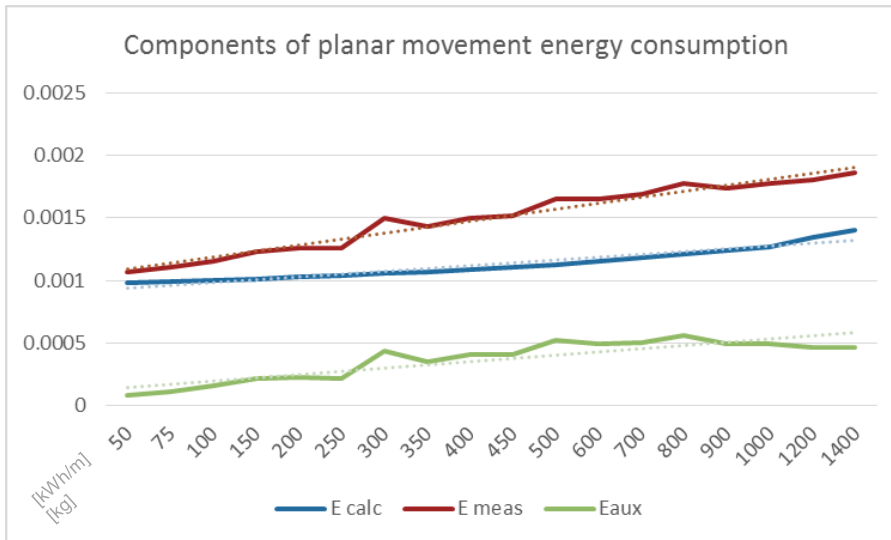


Figure 4-5: Components of planar movement energy consumption  
Source: Author

The development of increase of  $E_{meas}$  and  $E_{aux}$  corresponds to the increase of calculated energy consumption figures according to Figure 4-5 which shows evidence for the correctness of the generated values. As the measured values show increased energy consumption, simulations need to integrate auxiliary losses in the development of SECA figures.

#### Energy data for vertical movement

In accordance with the procedure of energy data verification in planar movement, energy consumption for lifting is analysed. Table 4-3 shows the data for cargo lifting in reference to an altering weight of lifted cargo. The general equation for potential energy serves as the reference basis, so that:

$$E_{pot} = m \cdot g \cdot h \quad (35)$$

where

g = gravity acceleration

h = height of lift

<b>additional payload [kg]</b>	<b>Potential Energy [Nm]</b>	<b>E<sub>L</sub> calc. [kWh]</b>	<b>E<sub>L</sub> meas. [kWh]</b>	<b>E<sub>aux</sub> [kWh]</b>
<b>50</b>	127.27	0.000035	0.000326	0.000291
<b>75</b>	151.75	0.000042	0.000345	0.000303
<b>100</b>	176.22	0.000049	0.000354	0.000305
<b>150</b>	225.17	0.000063	0.000369	0.000306
<b>200</b>	274.12	0.000076	0.000406	0.000330
<b>250</b>	323.07	0.000090	0.000429	0.000339
<b>300</b>	372.02	0.000103	0.000434	0.000331
<b>350</b>	420.97	0.000117	0.000464	0.000347
<b>400</b>	469.92	0.000131	0.000516	0.000385
<b>450</b>	518.87	0.000144	0.000550	0.000406
<b>500</b>	567.82	0.000158	0.000551	0.000393
<b>600</b>	665.72	0.000185	0.000615	0.000430
<b>700</b>	763.62	0.000212	0.000663	0.000451
<b>800</b>	861.52	0.000239	0.000717	0.000478
<b>900</b>	959.42	0.000267	0.000765	0.000498
<b>1000</b>	1057.32	0.000294	0.000932	0.000638
<b>1200</b>	1253.12	0.000348	0.000942	0.000594
<b>1400</b>	1448.92	0.000402	0.000980	0.000578

Table 4-3: Energy data validation vertical movement

Source: Author

Table 4-3 displays a difference from calculated to measured values, whereas Figure 4-6 shows the corresponding development of these values. The analytical evaluation of generated SECA data leads to the conclusion that the performed work includes a high degree of losses in comparison to the basic theoretical calculations. The development of process energy as split up by Figure 4-6 shows a logical and uniform increase of the calculated and the measured consumption values with a constant elevation of the auxiliary and loss energy in order to back up the accuracy and correctness of the generate SECA values.

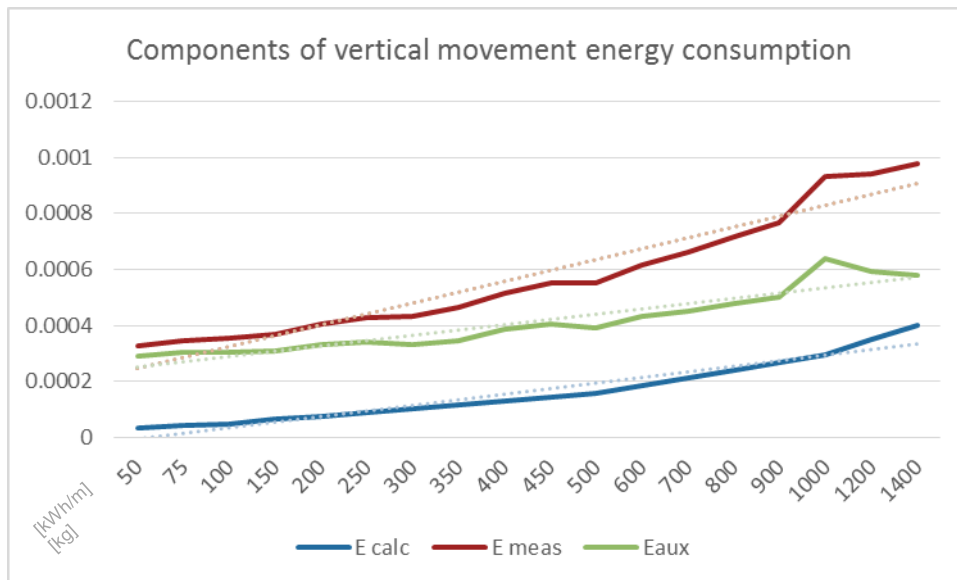


Figure 4-6: Components of vertical movement energy consumption

Source: Author

### 4.3 Process Data Collection

In an attempt to follow the multi method approach as per explanations of subsection 3.3 [p.58], the previously described data on process energy consumption are embedded into simulations based on quantitative process data. This quantitative investigation increases the informative value of the previous findings by categorising the implication and impact of the generated data, its interdependencies (Johnson and Onwuegbuzie 2004) and meaning to the examination results. The standardised and validated procedure decreases the researcher's subjective impact with the objective of increasing the significance of the research results.

The quantitative data collection of the pursued research approach focuses on the collection of process data in material supply in order to back up and further progress the energy consumption based findings into a large quantity source of information. The quantitative data is used to execute impact simulations based on a dedicated charging station allocation model, to investigate the influence to the material handling system energy balance and to number the potential for increased UBE by using occasional charging opportunities. The dedicated framework based on energy and process data as well as location-allocation modelling is described and validated in chapter 5 [p.105].

### **4.3.1 Process Data**

Process and Condition Monitoring deal with the systematic collection of data and information in reference to the organisation, control, execution and optimisation of in-house material flows, whereas the subsequent analysis and processing of results depends on the investigation's target definition (Wenzel and Bandow 2011).

In line with the executions of subsections 2.3 [p.15] and 2.4 [p.26] as well as the illustration of standardised material handling processes as per Figure 2-3 [p.20], investigations on the research subject have to enable the integration of energy data into quantitative process data by operating case study simulations. As per preceding explanations, material handling operations on man-guided material handling equipment consist of the repeating tasks of (1) approaching – unloaded driving, (2) pick up – free lift of cargo, (3) forwarding – loaded driving and (4) delivery – unloading or stacking. In reference to the research subject, aspects such as idle and break times, as well as the allocation of the named process functions constitute a relevant aspect to the potential evaluation. Referenced process data collection needs to record information in reference to the defined specifications and dedicated to the generation of valid and reliable results as indicated in the subsequent explanations.

### **4.3.2 Procedure of Process Data Collection**

The target of the executed process data collection is to generate the required information in reference to production related material handling processes as identified in the literature review of section 2.4 [p.26]. The required information on investigated processes includes travel times and distances, operating and idle times, as well as process routing.

The generation of process data was executed by the installation of data loggers on industrial forklift trucks. The used data loggers for process data collection were connected to an optical sensor within the 'Zeno Cam' system by the manufacturer 'Zeno Track'. The recorded optical information was used as basic information for the vehicle location determination. For the general system guidance, the investi-

gated facilities need to be equipped with markers attached to the floor or the existing rack system and entered into a correspondent marker file (see Appendix C) in order to serve as reference points for the position sensing.

Within the case study process data collection a minimum of 14 days were tracked in order to capture every day of a week for two times. With some vehicles, longer periods were tracked in order to evaluate whether an increased number of data sets increases the analysis information content. Process data collection was subdivided into several stages such as setup, testing and data collection. The setup part included the physical and software installation of the tracking system to the trucks of five days; the physical marker installation of one day and the writing of the marker csv-file of one day. The testing phase accounted for two more days as all vehicles needed to be tested within regular operation times. Due to physical marker damages and limitations in reference to the remote access to the tracking systems, final data collection took place from June 2015 till August 2015 inclusively.

While recording process operations, the following data is identified and recorded every 0.5 seconds:

- Vehicle ID
- Date and time
- Vehicle position within the Cartesian coordinate system
- Vehicle speed
- Loading condition (loaded / unloaded)
- Registration of a marker ID

The recorded csv-format can be exported to the favoured software format in order to process the subsequent analyses. For the pursued research approach, data was exported to Microsoft Excel in line with the analytical modelling process as per explanations of subsection 3.5.2 [p.84]. Table 4-4 shows a sample of the quantitative data being collected.

Date	Time	POSITIONX	POSITIONY	SPEED	LOADED	Marker ID
Day1	05:42:05,500	57.004	21.477	4.73	0	N12
Day1	05:42:06,000	57.105	19.826	0.66	0	N12
Day1	05:42:06,500	57.168	18.411	8.94	1	N12
Day1	05:42:07,000	57.228	16.989	9.16	1	0
Day1	05:42:07,500	57.201	15.488	9.59	1	0
Day1	05:42:08,000	57.076	13.983	9.62	1	K22
Day1	05:42:08,500	56.979	12.31	96	1	K22

Table 4-4: Example material handling process data

Source: Author

The systematic and structured generation of process data can be applied to any material handling process in order to collect process data and to generate the information being required to operate the developed research framework. Owing to the design of the investigation framework and its inherent process steps, other sources of equal information can also be used.

### 4.3.3 Process Data Validation

So as to achieve high quality and credibility of the generated research findings, collected data must be proved based on its consistency and replicability by individual examination (Saunders, Lewis and Thornhill 2009). Whereas the validation of energy data is based on measured data, its mathematical review and comparison to standard calculations, validation of process data refers to the examination of data plausibility.

Plausibility checking in reference to process data collection is executed in a four-step approach. In the first step, collected process data as displayed in Table 4-4 is recorded and converted into a movement and break time profile. In the second step these generated profiles are reviewed towards data consistency, so that skips and interruptions of data can be ruled out. The third step visually compares the generated movement profiles, respectively the break time profiles, and the production facility layout as per Figure 4-7, whereas the resolution of Figure 4-7 within this written output was kept low due to confidentiality reasons. In a fourth step, movement and break time profiles are presented and discussed with research environment experts in order to validate the plausibility of the results. The final step of data validation and plausibility testing as applied to the research execution is outlined by Saunders, Lewis and Thornhill (2009:298).



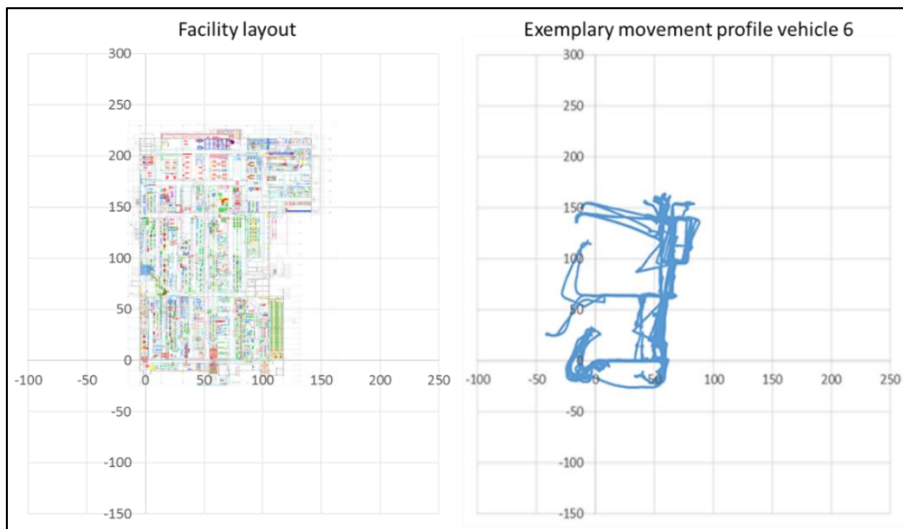


Figure 4-7: Visual process data validation

Source: Author

The qualitative data validation resulted in the exclusion of 37.95% of the collected case study process data in reference to the investigated operation shifts. The majority of excluded data sets resulted from inconsistent data or short record periods being evaluated as non-representative in the pilot implementation phase of data collection. The remaining set of 121 days of process data was evaluated as high quality data and considered for further investigations as executed in the case study investigations of chapter 6 [p.144].

#### 4.4 Chapter Summary

As per explanations on quantitative data collection, a broad set of data has been collected that is used to develop and design a simulation tool based on a location-allocation model later referred to as OCSLM (see chapter 5) in order to determine optimal charging station allocation for occasional recharging based on the integration of energy and process data. Data collection was first executed in pilot testing of the described approaches, meaning that validity, reliability and objectivity, as well as most efficient and effective usage of available resources were assured. Reliability of collected data, as well as the correspondent data collection procedures was presented throughout the explanations of this chapter by means of mathematical, logical and expert reviewing. Quality, reliability and availability justify the further usage of the generated data, so that the development and design of a subject specific location-allocation model based on these results is executed within the analysis design of chapter 5.

# CHAPTER 5

## ANALYSIS DESIGN

### 5.1 Introduction

The explanations of the following chapter describe the design of the developed Excel tool as part of the research project. This instrument forms the basis for the execution of system simulations in order to analyse the impact of occasional re-charging to the production related material handling energy balance and the possibilities for increased sustainable system design by optimised charging station allocation. The tool design integrates and, by this, establishes the realisation of the fundamental information and structures as being identified as a research gap within the scientific landscape throughout the comprehensive literature review of section 2.6 [p.33].

The tool, subsequently referred to as OCSLM as acronym for Occasional Charging Station Location Model, is a vital element of the pursued research project, since it solves the location-allocation problem by way of an iterative linear integer programming approach. Its reference to literature, basis on existing models for electric charging station locating and its methods are described first while defining the mathematical foundation and structure of OCSLM. Subsequently the composition and references of individual worksheets are explained. The sample calculations of section 5.3 [p.126] serve as verification and validation of the developed framework.

## 5.2 OCSLM foundation

The structure of OCSLM is based on the findings of the executed literature review as well as the methodological tools that are used to generate and analyse the results of the research project (see Figure 5-1).

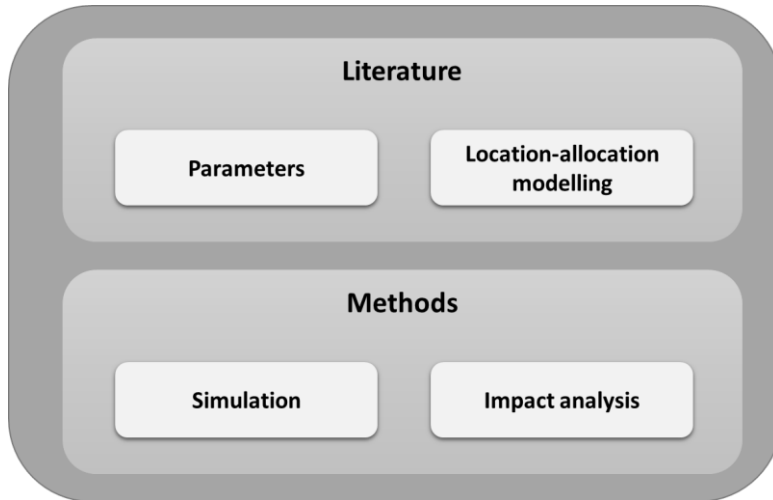


Figure 5-1 OCSLM foundation  
Source: Author

The identified performance indicators as per literature review with relevance to the research subject and as generated by the research data collection serve as fundamental parameters for the OCSLM development. Existing location-allocation models constitute a basis for the mathematical modelling and a structure for the simulation realisation. The results of the simulation, i.e. the proportion of energy being rechargeable by occasional recharging based on optimised charging station allocation for this specific application, exemplify the outcome value of the tool. The subsequent impact analysis is the method used to analyse and evaluate the potentials for more sustainable system design.

### 5.2.1 Parameters

The tool executions are based on the parameters as per identification of section 2.4 [p.26] for all further steps. In a first differentiation, considered parameters are referred to be whether input or output parameters. Input parameters in this applications are defined as values that result from process and process energy monitoring according to chapter 4 [p.89] and by this form the basis for the subsequent simulations in order to generate the output parameters. Output parameters rep-

resent the result of the pursued location-allocation solving and include the energetic and process related consequences of the realisation of occasional recharging. This procedure addresses the demand of Green Management to investigate the impact to energy and resource usage and by this enables a more thorough examination on the correlated CO<sub>2</sub> emissions as well as related costs in reference to the Lean target definition (see also section 2.2 [p.11]). In a second differentiation parameters are distinguished to be of ‘constant’ (c) or ‘variable’ (v) nature according to the following explanations:

- Constant parameters maintain the same value within the simulation and are defined exogenously. Alterations of these parameters change the fundamentals of the case study simulation and need to be handled as separate cases.
- Variable parameters can alternate within a certain range of values within an individual case study. Changing variable parameters can impact basic data of other variable parameters. The simulation design integrates the impact from changing variable parameters. For example, changing the average weight of handled goods will be of direct impact on the energy consumption of translational or lifting material movements.

Table 5-1 depicts the parameters with importance to the simulation design which are classified for the further progress of this research according to their material handling system affiliation. The identified parameters are assigned to ‘Handling Equipment Data’, ‘Process Data’ or ‘Energy Supply Data’.

<i><b>Dimension</b></i>	<i><b>Parameter</b></i>	<i><b>Unit</b></i>	<i><b>Nature</b></i>
<i><b>Handling Equipment</b></i>	Energy consumption planar movement	kWh/m	Variable
	Energy consumption vertical movement	kWh/0.1m	Variable
	Vehicle mass	kg	Constant
	Battery mass	kg	Variable
<i><b>Process</b></i>	Drive distance	meter	Variable
	Routing	(x ; y)	Constant
	Velocity	m/s	Variable
	Number/duration of breaks per position	- / s	Constant
	Number/weight of shipments	- / kg	Constant
	Number of stacked shipments	-	Constant
<i><b>Recharge Energy</b></i>	Power transfer performance $p_T$	kW	Constant
	Power transfer efficiency $\eta_T$	%	Constant
	Charging potentials within range $S_{ij}$	-	Variable

Table 5-1: Simulation parameter categorisation  
Source: Author

Parameters have been classified according to their system affiliation and system origin in order to structure the simulation design. The research integration of individual parameters is explained within the descriptions of OCSLM simulation realisation of subsection 5.3.1.

The generated output parameters, i.e. the results of the simulation, are processed within the impact analysis in line with the research target definition and the predictive validation approach (see section 4.3.3 [p.103]). The output parameters and derived results as per Table 5-2 address the demand and requirements to information content and increased system sustainability as per executions of chapter 2 [p.9].

<i><b>Dimension</b></i>	<i><b>Parameter</b></i>	<i><b>Unit</b></i>
<i><b>Handling Equipment</b></i>	Total energy consumption	kWh
	Charging potential	kWh
	Battery mass required	kg
	Battery capacity required	kWh
	Reduction process energy	%
	Savings CO <sub>2</sub> emissions battery	kg
<i><b>Process</b></i>	Additional drive distance	m
	Additional energy consumption movement	kWh
	Savings CO <sub>2</sub> emissions process	%
<i><b>Recharge Energy</b></i>	Rechargeable energy	kWh
	Transmission losses	kWh

Table 5-2: Research output parameters  
Source: Author

### **5.2.2 Occasional charging station location modelling**

Within the investigations on occasional recharging not all existing demand points can and shall be considered as the target is to efficiently maximise the additional energy input. MCLP approaches ensure the coverage maximisation whilst keeping efficiency high due to the negligence of demand spots that are considered to be less beneficial.

Proceeding with an MCLP based approach in reference to energetic system integration requires the integration of several aspects with impact to the calculation algorithm and by this to the simulation design. The following explanations form the structured approach of executing and adapting the general MCLP approach

to the research design. The research approach of OCSLM as per Figure 5-2 was developed with dependence on existing design approaches in order to systematically address the specific research target. Specific term definitions, as well as explanations on research design, including considered mathematical equations are stated within the executing chapters. Research requirements were addressed in respect to demand modelling based on the executions of Eiselt, Laporte and Thisse (1993); the research spatial representation of Plastria (2001); the development of the underlying utility function referring to the executions of Drezner and Eiselt (2002); the cost determination by Eiselt, Laporte and Thisse (1993) and the definition of the competition objective according to Eiselt and Marianov (2015).

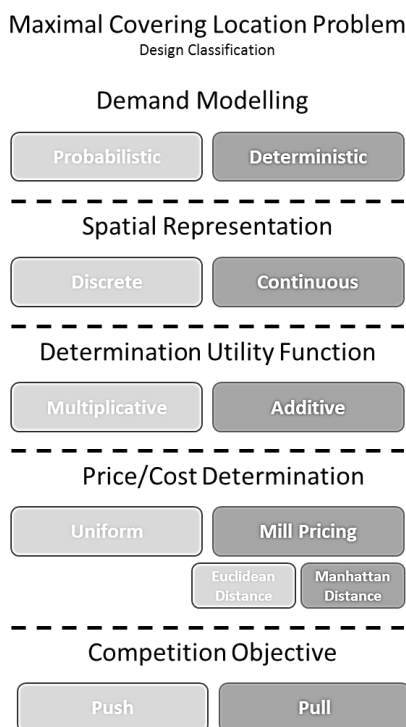


Figure 5-2: Structured MCLP development approach  
Source: Author

The basic MCLP model according to Church and ReVelle (1974) of section 2.5 [p.29] is adapted to the research requirements while following the design classification steps.

The application of OCSLM seeks to maximise the usable break times that can be used for additional recharging by a given number of contactless charging stations for occasional recharging for an investigated vehicle or fleet of vehicles (see also Giménez-Gaydou et al. 2016). The location(s) of integrated break times shall be situated within a defined (energy efficient) range in order to address the demand

for an endogenous determination of the covering distance. The mathematical formulation of OCSLM is stated as below:

$$\max \sum_{i \in I} a_i \cdot z_i \quad (36)$$

$$s.c. \quad \sum_{j \in N_i} x_j \geq z_i \quad \forall i \in I \quad (37)$$

$$\sum_{j \in J} x_j = c \quad (38)$$

$$x_j = (0,1) \quad \forall j \in J \quad (39)$$

$$z_i = (0,1) \quad \forall i \in I \quad (40)$$

$$S_{ij} = (0,1) \quad \forall i \in I; \forall j \in J \quad (41)$$

$$E_{ij} = (t_i - 2 t_{d_{ij}}) \cdot p_t \cdot \eta_t - 2 \cdot d_{ij} \cdot E_{cd} \quad (42)$$

where

I = defines the set of demand nodes (= location(s) of break times)

i = location of demand node in  $(x_i; y_i)$

J = defines the set of charging sites within  $(x_{\min}; y_{\min}) \cup (x_{\max}; y_{\max})$

j = location of charging station(s) in  $(x_j; y_j)$

$a_i$  = demand in point I (=additional recharging time)

$x_j = \begin{cases} 1 & \text{if a charging station is allocated within energy efficient range } S \text{ to a site } j \\ 0 & \text{otherwise} \end{cases}$

c = number of sites (= charging stations) to be located

$S_{ij} = \begin{cases} 1 & \text{if } E_{ij} > 0 \\ 0 & \text{otherwise} \end{cases}$

$E_{ij}$  = additional energy input in j by integrating additional recharging time  $a_i$  from I

$t_i$  = usable break time in i

$t_{d_{ij}}$  = driving time from i to j

$d_{ij}$  = distance from i to j

$p_t$  = performance of energy transmission

$\eta_t$  = transmission efficiency

$E_{cd}$  = energy consumption of planar handling (SECA)

$$N_i = \{j \in J \mid d_{ij} \leq S\}$$

$N_i$  defines the set of stations that cover the usable break times in reference to  $S$  in site  $i$ . A demand location, i.e. a location where a break time exists, is supposed to be covered in case that the sum of additional energy input and energy effort in order to reach a charging station is positive according to the definition of  $E_{ij}$ . Equivalent to this a demand point  $i$  is uncovered in case that the closest charging station is at greater energetic effort than the potential, additional input, so that  $E_{ij} < 0$ .

The primary target is to maximise the additional energy input, i.e. coverage, in reference to the limitation to a given number  $c$  of charging stations (see constraint (38)) under the specification of a positive contribution to the overall energy balance. Based on the specifications by Berman, Drezner and Krass (2010) and Giménez-Gaydou et al. (2016), the model allows continuous charging station allocation within the investigated geographic array. In accordance with this, equation (37) restricts the binary factor  $z_i$  to equal 1 in case of one or more charging station(s) of the set  $N_i$  being within positive range  $S_{ij}$  to the investigated location  $i$ . Constraint (39) and (40) define the variables  $z_i$  and  $x_j$  to be of binary character.

The equations (41) and (42) realise the integration of an endogenous covering distance function.  $S_{ij}$  is defined as a binary function to be set to 1 if the demand spot in  $j$  positively contributes to  $E_{ij}$  in  $i$ , so that  $E_{ij} > 0$ ; and 0 otherwise. The binary integration of a static charging spot with positive contribution to the system energy balance fulfils the requirement set up by Frade et al. (2011). (42) defines the impact of surrounding demand spots to the energy balance by vehicles approaching at charging station locations from usable idle time locations. The integration of partial charging times is based on the model by Berman, Drezner and Krass (2010). The realisation of the functional driving distance as a utility function can only be realised based on the detailed knowledge about energy consumption as generated by the SECA energy consumption values of section 4.2 [p.89]. The definition of a positive contribution to the energy balance is not possible without this definition and knowledge.



The following explanations according to the design classification clarify further specifications and characteristics of the research data analysis and optimisation approach.

### 5.2.2.1 Demand Modelling

An imperative part of Location Planning consists of the modulation of demand and its quest for satisfaction. The demand in the pursued research is represented by process related break times in reference to the target of detailed process data integration in line with Xi, Sioshansi and Marano (2013). The location in which a break time occurs represents the location of demand, meaning that the duration of all accumulated break times in one location equals the total demand in that spot. Locations with long break times and, by inference, high demand have higher impact to the charging station allocation determination according to equation (36), meaning that the break time duration presents a weighting factor for allocation determination. The demand  $a_i$  can be integrated into simulations by using either deterministic or probabilistic models (Eiselt, Laporte and Thisse 1993).

Probabilistic models neglect the possibility of an explicit allocation of demand and by this use a stochastic distribution to the number of facility sites. In reference to (41), demand points within energy efficient range, i.e. within the captured area, to charging stations are dedicated to these sites. The coverage of this demand spot by a second charging station is target to be avoided. By this,  $S_{ij}$  defines the dedication of demand points to the charging site(s) within positive range in order to generate the site allocation with the highest energetic benefit for the investigated system. (43) defines the additional energy input in location  $j$  in reference to a deterministic modulation of demand.

$$E_j = (t_j \cdot p_t \cdot \eta_t) + \sum_{j=1}^i (t_i - 2 t_{d_{ij}}) \cdot p_t \cdot \eta_t - 2 \cdot d_{ij} \cdot E_{cd} \quad (43)$$

$$(x_{opt} / y_{opt}) = arg \max E_j \quad (44)$$

$$s.c. \quad S_{ij} > 0$$

Formula (43) defines the energy input in  $j$  for the investigated number of handling equipment, i.e. the fleet, so that after the determination of the most beneficial charging station allocation(s) the simulation needs to draw back the impact to individual vehicles. This results in the need to integrate additional travel distances

and travel times within process routing in reference to the approach of Upchurch, Kuby and Lim (2009) as per explanations of subsection 2.6.1 [p.36]. This procedure integrates the aspect that the most beneficial allocation in reference to the set of investigated equipment of a system must not necessarily be the optimum allocation in reference to a single vehicle of a fleet. Formula (44) defines the location to be optimised in order to maximise the additional energy input in  $E_j$ .

#### 5.2.2.2 Spatial Representation

An additional differentiating factor of the developed model to existing research is the question of continuous or discrete positioning within the research setting (ReVelle and Eiselt 2005; Plastria 2002). In the described research area this is limited to the two-dimensional space.

Discrete modelling refers to the restriction of  $j$  to pre-defined locations within the research environment. Considering that the integration of charging stations is often of subordinate relevance in warehouse design, locations of implementation for conventional chargers are often limited to specific areas. As the investigation targets to implement charging stations within process structures, a limitation to pre-defined locations prevents the energy optimal system integration, so that a continuous location-allocation is performed which allows station integration in any spot within the investigated area ( $x_{\min} \rightarrow x_{\max}$ ;  $y_{\min} \rightarrow y_{\max}$ ). Applying the developed algorithm to other system settings, continuous modelling can also be limited to line, curve, route or circular modulation.

#### 5.2.2.3 Determination Utility Function

Drezner and Eiselt (2002:155) suggest formulating a Utility Function ( $U_{ij}$ ) in order to ensure the integration of all impact factors to Location Planning. The Utility Function calculates the benefit of an installation in  $j$  from the demand in  $i$ , whereas  $U_{ij} = f(q_i, h_j, d_{ij})$ . By doing so, the benefit for the demand point in  $i$  by the facility in  $j$  depends on the quality of demand  $q_i$  in  $i$ , the characteristics  $h_j$  of the facility in  $j$ , as well as the distance  $d_{ij}$  from facility location to the investigated demand point  $i$  (Drezner and Eiselt 2002:155). Additive Utility Functions calculate the benefit by merely adding rated individual factors in order to calculate the total benefit in  $i$ . To calculate the benefit in  $i$ , the distance decay parameter  $\lambda$  is introduced in order to consider the impact of distance  $d_{ij}$  to the investigations, so that in line with

Koenig (1980), Cervero, Rood and Appleyard (1999) and Handy and Niemeier (1997) the Utility Factor can be calculated as per (45).

$$U_{ij} = f(q_i, h_j, d_{ij}) = -d_{ij} \cdot \lambda + q_i \cdot h_j \quad (45)$$

In order to adapt the Utility Function to the research design the integrated parameters are specified, so that distance decay parameter  $\lambda$  equals the energy consumption for material handling equipment to approach the charging station ( $\lambda = 2 \cdot E_{cd}$ ) and the factor  $h_j$  represents the characteristics of the charging facility which includes energy transmission performance and efficiency, so that  $h_j = p_t \cdot \eta_t$  defines the quality of demand when reaching in  $j$ , so that  $q_i = t_i - 2 t_{d_{ij}}$ .

Consequently:

$$\begin{aligned} U_{ij} &= -d_{ij} \cdot \lambda + q_i \cdot h_j \\ &= -d_{ij} \cdot 2 \cdot E_{cd} + (t_i - 2 t_{d_{ij}}) \cdot p_t \cdot \eta_t \end{aligned} \quad (46)$$

The comparison of (42) and (46) shows that  $U_{ij} = E_i$  in  $j$  as being part of  $E_j$ . By this the utility function shows the validity of  $E_j$  as being defined as an endogenous function for a positive energy input.

#### 5.2.2.4 Cost determination

Cost determination in conventional Location Planning is concerned with the impact of price level to demand as well as the influence on location's turnover for which Eiselt, Laporte and Thisse (1993) defined two impact models based on different pricing assumptions:

- Price impact to demand coverage is low, so that location affiliation is based on the location itself, i.e. distance from  $i$  to  $j$
- Price impact to demand coverage is high, so that price level AND location impact demand coverage

In accordance to the afore-mentioned impact models, different pricing strategies are possible. These include:

- Uniform pricing with identical prices without reference to transport cost
- Spatial price discrimination with different price levels in alternating locations
- Mill-Pricing as the sum of unit price and transport cost

Adapting the pricing models and strategies to the pursued research design, price level equals the function of energy transfer of charging infrastructure including

transmission performance ( $h_j$ ). Cost of transportation equals the additional energy consumption for approaching the charging infrastructure ( $E_{cd}$ ). From the definition of  $S$  it can be seen that a high value of  $h_j$  increases the beneficial range around  $j$ . Referring to the Mill-Pricing approach, this adaption shows a positive impact of increasing  $h_j$  towards range extension and integrates the range reduction by the impact of transportation cost.

The definition of  $d_{ij}$  for determining the energy consumption for charging station approaching refers to the Manhattan Distance Modell as per (47). Corridors and halls in warehouses and facilities are arranged in rectangular squares, so that the representation of distances from  $i$  to  $j$  needs to be integrated respectively, so that:

$$d_{ij}(x, y) = |x_j - x_i| + |y_j - y_i| \quad (47)$$

#### 5.2.2.5 Competition Objective

The Competition Objective defines the basic target of sites as elements of  $J$  and by this the balance of locations to each other, so that Eiselt and Laporte (1995) differentiate among push and pull objectives.

Push Objectives arrange facilities with biggest possible distance, so that Pull Objectives are used for the research design. These define the locations to be situated closest to the demand in respect to location weighting as expressed by the factor  $a_i$  in (36), minimisation of distances  $d_{ij}$  and maximisation of the additional energy input, so that the Pull Objective is defined as a mini-max application within the pursued research.

### 5.2.3 Simulation methodology

The target of a simulation is to investigate a real system in detail by the creation of a substituting model in order to analyse the system behaviour, whereas simulation accuracy needs to be assured. The advantage of simulations is the possibility to easily manipulate and control the research setting, such as the acceleration of time sequences without violating any ethical principles. Furthermore, simulations bear the advantage of lower cost in comparison to real system applications as well as lower or no negative impact from system failures and manipulations to the real system (Evans and Olson 2002).

The formal basis of simulations are mathematical functions and relations that define the structure and interrelation of system parameters and, in this way, system behaviour. As per the defined research target of section 3.2 [p.57], the outlined methodology has to identify charging station allocations for optimised additional energy input to the investigated material handling system based on the previous definitions and requirements. The basic formula for the identification of these spots is given by equation (43):

$$E_j = (t_j \cdot p_t \cdot \eta_t) + \sum_{j=1}^i (t_i - 2 t_{d_{ij}}) \cdot p_t \cdot \eta_t - 2 \cdot d_{ij} \cdot E_{cd}$$

$E_j$  adds together the integrable and positively contributing demand spots to the rechargeable energy in the possible charging station location in  $j$ . This amount of energy consists of two elements. The first component is the energy yield in  $j$  in reference to the net idle time:

$$E_j = (t_j \cdot p_t \cdot \eta_t) \quad (48)$$

(48) describes the possible energy input for the case that  $j = i$ , so that the location of a charging station in  $j$  is also the location of an occurring idle time in  $i$ .

The second component consists of the surrounding idle times that allow the approaching of vehicles to the charging stations without disturbance of the process sequencing:

$$E_{ij} = \sum_{j=1}^i (t_i - 2 t_{d_{ij}}) \cdot p_t \cdot \eta_t - 2 \cdot d_{ij} \cdot E_{cd} \quad (49)$$

The requirements to this approaching procedure is the positive contribution to the energy balance, so that  $E_{ij} > 0$ , as well as no disturbance of the process sequencing. The second requirement determines the approaching process to be operated only if charging station approaching and returning to the initial demand spot can be executed within the available process idle time (see subsection 5.2.3.2).

The following explanations demonstrate the research execution in reference to the basic mathematical formulation of OCSLM and the integration into the simulation design.

### 5.2.3.1 Net idle time

The net idle time is defined as the time that a vehicle is located in the spot  $i$  with a defined vehicle velocity  $<0.05\text{m/s}$ . This classification terms  $i$  as location of break

time and by this as being a demand spot. The complete volume of net idle time can only be used for occasional charging if  $i$  is also the location of  $j$ . If  $j \neq i$ , several reductions need to be made according to 5.2.3.2.

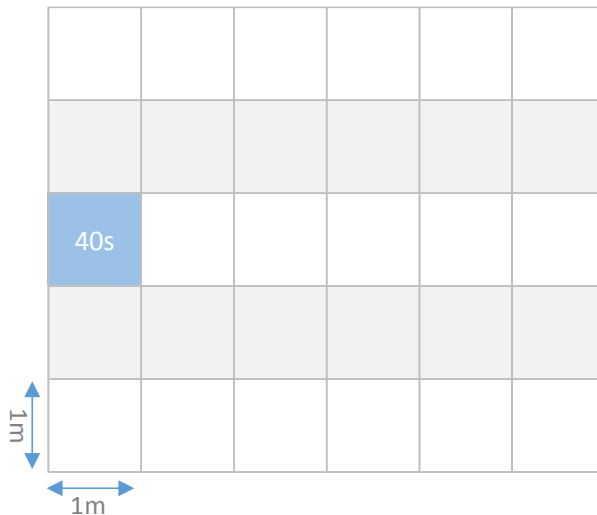


Figure 5-3: Net idle time  
Source: Author

Figure 5-3 shows the schematic presentation of a production facility as being part of a Cartesian coordinate system with the raster graduation of 1m x 1m. The blue coloured box represents the occurrence of a break time of 40 seconds ( $t_i = t_j = 40\text{sec}$ ) in reference to the determined x- and y- coordinate that are of minor relevance at this point. Under the assumption of the transmission performance  $p_i$  to be 3.6kW and a transmission efficiency  $\eta_i$  of 90%, the net idle energy input in  $i$  can be calculated in reference to (48), so that:

$$E_i = (t_i \cdot p_i \cdot \eta_i)$$

$$E_i = (40s \cdot 3.6kW \cdot 0.9)$$

$$E_i = 129.6 \text{ kW} \cdot \text{s} = 0.036 \text{ kWh}$$

This calculation shows that in case of  $i = j$  a total of 0.036kWh can be recharged to the vehicle battery.  $E_i$  is subject to energy reduction in case of  $i \neq j$  as per the following explanations.

### 5.2.3.2 Relocated idle times

Idle times as per previous explanations are subject to relocation in case that  $i \neq j$  and  $E_{ij} > 0$  as per equation (42). This means that all idle times of a cell are relocated to its neighbouring cell(s) under the consideration of diminishing factors in order to determine the charging station allocation with the maximal additional energy input. Negative impact to the relocation of idle times emerges due to approaching and returning times of a vehicle from spot  $i$  to  $j$  in order to maintain the initial process sequence as well as additional energy consumption by the vehicle in reference to the additional driving distance for this approaching and returning operation. The relocation of idle times, being realised within corridors, actively impairs the vehicle routing due to the relocation of the vehicle location(s), whereas there is no process disturbance to the production related main processes. Figure 5-4 shows the technical relocation of idle times from demand spots to the charging station location  $j$ .

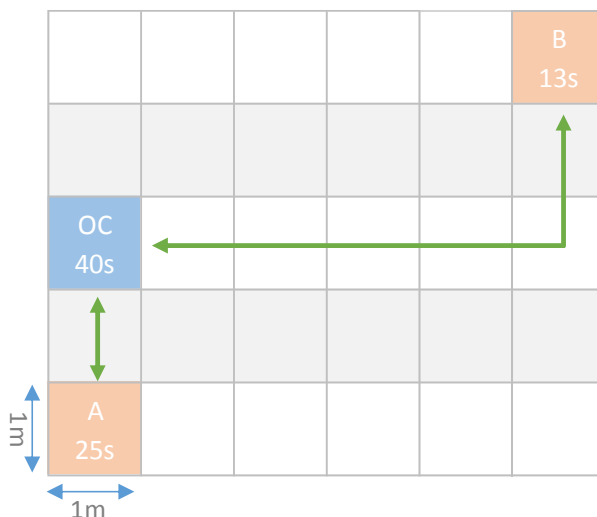


Figure 5-4: Relocated idle times  
Source: Author

The distance from demand spot A to the occasional charging station (OC) is determined to be 1m, whereas the distance from B to OC is 6m. Direct approaching of charging stations is neglected in line with the rectangular arrangement of production facility layout and the determined reference to the Manhattan Distance Model as per 5.2.2.4.

Under the assumption of an average vehicle velocity of 1m/s, the remaining charging time for the relocation from A ( $= i$ ) to OC ( $= j$ ) can be calculated.

$$(t_i - 2t_{dij}) = (25\text{sec} - 2 \cdot 1\text{sec}) = 23 \text{ seconds}$$

In reference to this, only 23 seconds of the initial 25 seconds can be used in  $j$  in order to recharge the vehicle battery and to not disturb the main process sequence, meaning that in reference to charging performance and efficiency a total of 0.0207 kWh can be recharged. This value is subject to additional energy consumption which is required for the planar movement of the unloaded vehicle from A to OC and back to the initial point in A in reference to the SECA energy consumption value ( $E_{cd} = 0.00034 \text{ kWh/m}$ ), so that:

$$2 \cdot d_{ij} \cdot E_{cd} = 2 \cdot 1\text{m} \cdot 0.00034 \frac{\text{kWh}}{\text{m}} = 0.00068 \text{ kWh}$$

For the relocation of A to OC, the total energy contribution is:

$$((25\text{sec} - 2 \cdot 1\text{sec}) \cdot 3.6\text{kW} \cdot 0.9) - \left(2 \cdot 1\text{m} \cdot 0.00034 \frac{\text{kWh}}{\text{m}}\right) = 0.02 \text{ kWh}$$

For the relocation of demand point B to OC, the energy balance is:

$$((13\text{sec} - 2 \cdot 6\text{sec}) \cdot 3.6\text{kW} \cdot 0.9) - \left(2 \cdot 6\text{m} \cdot 0.00034 \frac{\text{kWh}}{\text{m}}\right) = -0.00318 \text{ kWh}$$

The sample calculations show that the relocation of the idle time in B, i.e. the approaching from B to the charging station, results in no positive energy input respectively in increased energy consumption, whereas the relocation of A is evaluated to have a positive contribution to the system energy balance.

### 5.2.3.3 Multiple idle time relocation

Discrete models (see Figure 5-5-a) as used by Berman, Drezner and Krass (2010) and Frade et al. (2011) relocate charging stations among the predefined locations of occurring idle times. The result is the charging station allocation in C as being characterised by the highest ratio of chargeable energy. In reference to continuous location-allocation modelling as per Figure 5-5-b, intermediate locations may result in an equal or higher ratio of energy input in line with the pursued system optimisation target.



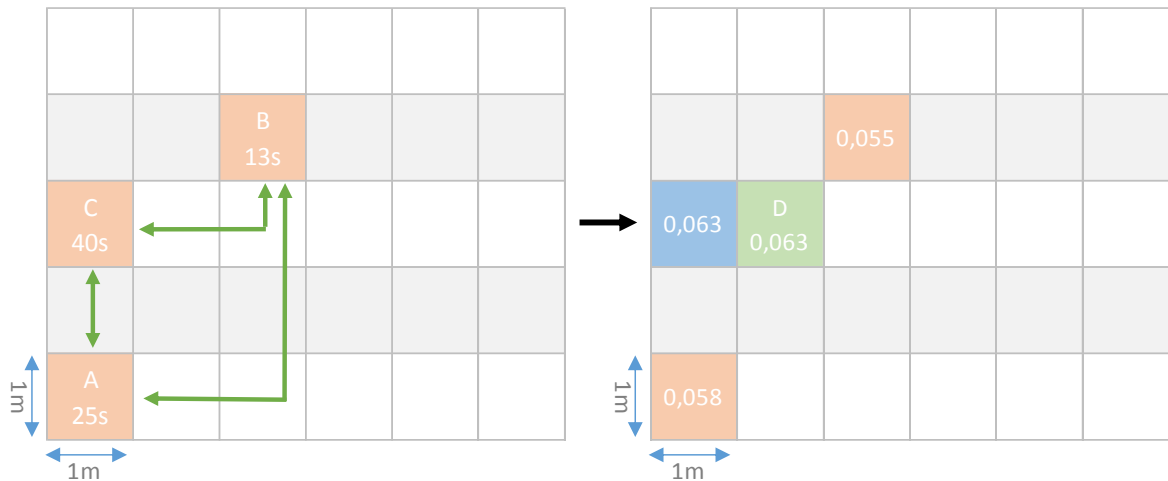


Figure 5-5: Charging station allocation a) time based discrete modelling b) energy based continuous modelling Source: Author

Based on equation (43), the relocation of idle times shows the results as displayed in Figure 5-5 and highlights the existence of equally or more beneficial allocation spots:

$$E_A = \frac{(25s \cdot 3.6kW \cdot 0.9)}{3600} + \frac{((40s - 2 \cdot 1s) \cdot 3.6kW \cdot 0.9)}{3600} - \left(2 \cdot 1m \cdot 0.00034 \frac{kWh}{m}\right) + \frac{((13s - 2 \cdot 4s) \cdot 3.6kW \cdot 0.9)}{3600} - \left(2 \cdot 4m \cdot 0.00034 \frac{kWh}{m}\right) = 0.058 \text{ kWh}$$

$$E_B = \frac{(13s \cdot 3.6kW \cdot 0.9)}{3600} + \frac{((40s - 2 \cdot 2s) \cdot 3.6kW \cdot 0.9)}{3600} - \left(2 \cdot 2m \cdot 0.00034 \frac{kWh}{m}\right) + \frac{((25s - 2 \cdot 4s) \cdot 3.6kW \cdot 0.9)}{3600} - \left(2 \cdot 4m \cdot 0.00034 \frac{kWh}{m}\right) = 0.055 \text{ kWh}$$

$$E_C = \frac{(40s \cdot 3.6kW \cdot 0.9)}{3600} + \frac{((13s - 2 \cdot 2s) \cdot 3.6kW \cdot 0.9)}{3600} - \left(2 \cdot 2m \cdot 0.00034 \frac{kWh}{m}\right) + \frac{((25s - 2 \cdot 1s) \cdot 3.6kW \cdot 0.9)}{3600} - \left(2 \cdot 1m \cdot 0.00034 \frac{kWh}{m}\right) = 0.063 \text{ kWh}$$

$$E_D = \frac{(40s \cdot 3.6kW \cdot 0.9)}{3600} + \frac{((13s - 2 \cdot 1s) \cdot 3.6kW \cdot 0.9)}{3600} - \left(2 \cdot 1m \cdot 0.00034 \frac{kWh}{m}\right) + \frac{((25s - 2 \cdot 2s) \cdot 3.6kW \cdot 0.9)}{3600} - \left(2 \cdot 2m \cdot 0.00034 \frac{kWh}{m}\right) = 0.063 \text{ kWh}$$

The relocation of demand spots to a centralised charging station is based on the integration of usable idle times, meaning that the individual duration of available charging times is integrated as weighting factor  $a_i$  in equation (36). This allocation approach integrates the possibility of a charging station to be allocated in a spot  $j$ , where there is no demand spot  $i$ , but is evaluated to be the most beneficial

integration spot in reference to the overall energy balance. The simulation design assures the single relocation of all demand spots in reference to data validity.

#### 5.2.3.4 Vehicle velocity definition

The definition of vehicle velocity is an important part as it has several areas of influence to the simulation design. In reference to vehicle mass and transported payload, vehicle velocity impacts the energy consumption as higher speeds result in increased energy demand for planar movement. The development of energy consumption figures in reference to SECA is executed in subsection 4.2.1 [p.90].

Additionally, as per the definitions of subsection 5.2.3.2, travel speed influences the calculated approaching time of vehicles to charging stations. Higher travel speeds result in increased charging times, but refer to increased energy consumption for approaching.

Process data collection of subsection 4.3.2 [p.101] shows the process allocation data being recorded twice per second. Due to relatively low vehicle velocity successive locations are assumed to be in direct sequence and linear distance so that vehicle velocity is calculated by the following equation:

$$v = \frac{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}{2s} \quad (50)$$

#### 5.2.3.5 Matrix development

The simulation of system operations includes the processing of individual and fleet simulations, so that individual and fleet analyses are combinable within the investigation executions. In order to assure a comprehensive examination, different results, being displayed in different matrices as per explanations of section 5.3, need to be integrated and combined in order to generate the target outcome. The mathematical combination of simulation values is based on:

$$A + B = (a_{ij}) + (b_{ij}) = (a_{ij} + b_{ij}) \quad (51)$$

So that for example:

Matrix A	Matrix B																																																																	
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5	0	0	3	1	7																																																													

Figure 5-6: Example matrix combination

Source: Author

### 5.2.4 Impact analysis

The target of impact analyses is to examine the changed outcome resulting from particular interventions to an investigated object (Scriven 2008). The impact evaluation focuses on the execution of a cause-and-effect analysis in order to determine the changes from alternative operations to the system performance and its meaning for system design.

The executed simulations on charging station allocation for occasional recharging generate system allocations and number the impact from system integration to the system energy balance. The resulting values refer to additional energy input, additional energy consumption, additional losses that are subject to impact analysis in order to draw conclusions from system implementation to increased resource efficiency and sustainability.

The impact from additional available energy allows system adaptations such as battery downsizing with influence to the variable research parameters as per subsection 5.2.1 [p.106]. This self-reinforcing effect requires the realisation of a multi-step approach including specific calculation loops in order to evaluate the potential of system integration (see Figure 5-7).

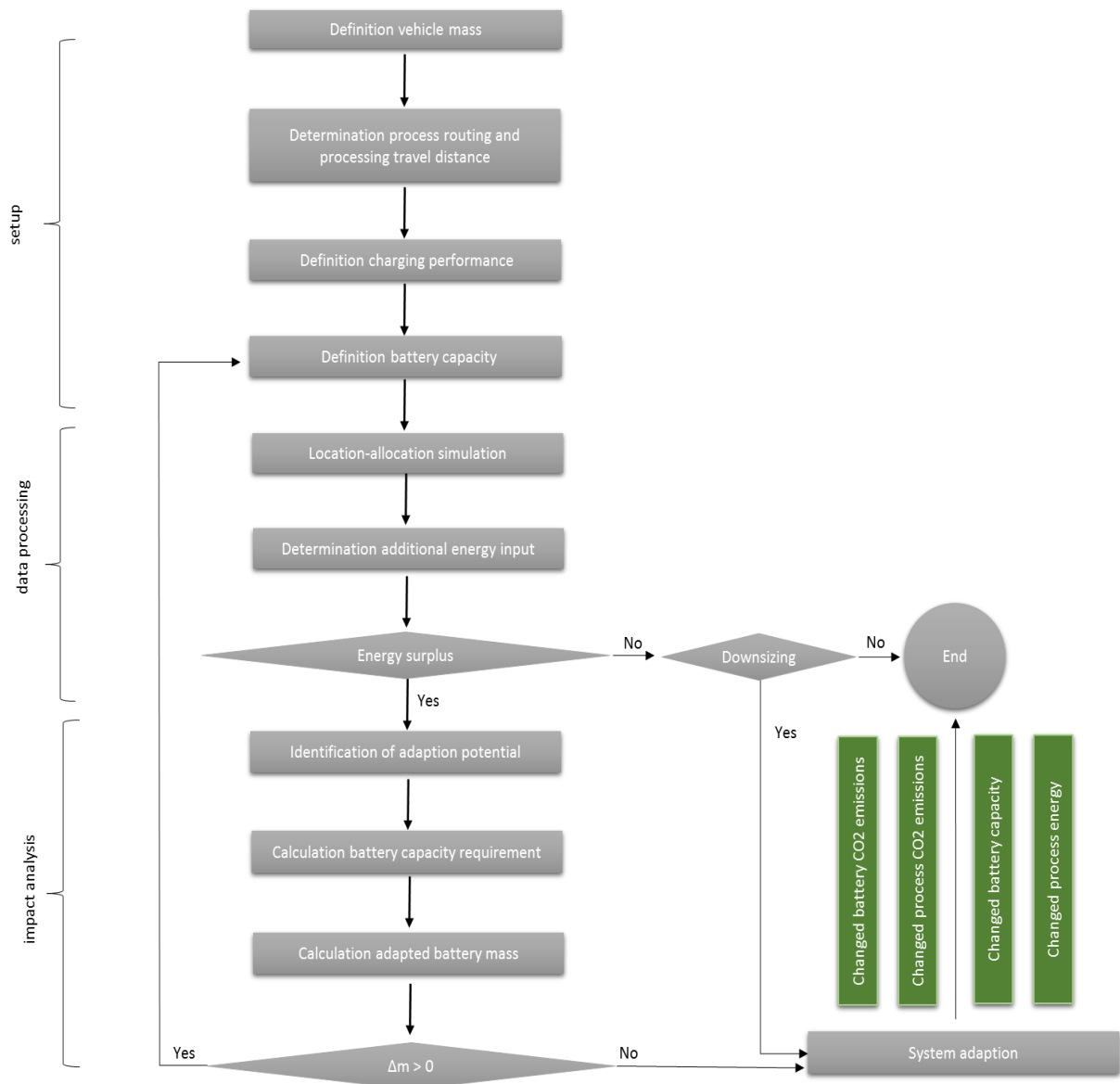


Figure 5-7: Impact analysis

Source: Author

For the execution of the impact analysis, simulation results such as total drive distance, average velocity, additional drive distance and the usable charging time respectively the volume of chargeable energy ( $E_{rech}$ ) are used as input for the impact analysis. Additional information is given by the simulation pre-settings such as battery capacity ( $C_{bat}$ ) and mass, total vehicle mass, average weight of carried payload, battery related energy density and depth of discharge (DoD) as well as charger characteristics such as transmission performance and efficiency.

In the initial step the Usable Battery Energy is calculated by

$$UBE = C_{bat} \cdot DoD \quad (52)$$

From the battery and vehicle mass as well as average process velocity, the SECA values for planar movement are determined in order to calculate the process energy consumption ( $E_{cw}$ ) in reference to the total drive distance and lifting movements as input from process simulations.

From the amount of energy being rechargeable in reference to usable idle times, the downsizing potential is calculated by integrating the impact from DoD:

$$C_{bat-reduction} = C_{bat} - \left[ (UBE + E_{rech} - E_{cw}) \cdot \frac{1}{DoD} \right] \quad (53)$$

The multiplication of (53) with the specific energy density of the considered battery technology (here lithium ion with 0.15kWh/kg) results in the battery mass that is subject to downsizing. The reduced battery mass itself effects the total energy consumption due to a lower total mass to be carried within planar movement, so that the described calculation cycle needs further execution(s) until the battery mass is not subject to further mass reduction (see Figure 5-7). The total amount of attainable battery mass reduction is summed up in order to calculate the total reduction of battery mass and capacity, as well as energy consumption savings achieved due to  $\Delta m_{bat}$  in order to address the demand for increased resource conservation. The impact to sustainability is referred to by the saved emissions on CO<sub>2</sub> based on the reduced emissions of battery manufacturing (75,000g per kWh battery capacity – Dell’era et al. 2015) as well as reduced process energy consumption (564g per kWh battery energy – Kranke, Schmied and Schoen 2011). The additional drive distance, i.e. the energy consumption for charging station approaching, and non-usable idle time as expression of process imminent losses are considered and integral part of this concluding investigation.

For calculation verification the below sample calculation illustrates the 1st-cycle calculation:

<b>Battery Capacity</b>	<b>V</b>	<b>Ah</b>	<b>kWh</b>
	48	300	14.4
<b>Battery Weight</b>	96	<b>kg</b>	
<b>Process Drive Distance</b>	11,970	<b>m</b>	
<b>Vehicle Speed</b>	1.39	<b>m/sec</b>	
<b>Total vehicle mass</b>	2,301.8	<b>kg</b>	
<b>Lifted Mass</b>	600	<b>kg</b>	
<b>Additional driving distance</b>	270	<b>m</b>	
<b>Energy Density (Li)</b>	0.15	<b>kWh/kg</b>	
<b>Depth of Discharge</b>	85	<b>%</b>	
<b>Total process energy consumption</b>	10.25	<b>kWh</b>	

<b>Charger Power Rating</b>	<b>Volts</b>	<b>Amp</b>
	48	75
<b>Charging Time/ day</b>	2.5	<b>hrs</b>
<b>Efficiency of Charger</b>	89	<b>%</b>
<b>Number of chargers installed</b>	3	<b>pcs</b>
<b>Recharge energy</b>	8.01	<b>kWh</b>

Table 5-3: Basic data exemplary battery mass reduction calculation

Source: Author

In reference to (52) usable battery energy is determined by

$$UBE = C_{bat} \cdot DoD = 14.4kWh \cdot 85\% = 12.24kWh$$

The battery reduction can be calculated in reference to (53) and an initial SECA energy consumption for planar movement of 0.00086kWh/m at an average velocity of 1.39m/s:

$$\begin{aligned} C_{bat-reduction} &= C_{bat} - \left[ (UBE + E_{rech} - E_{cw}) \cdot \frac{1}{DoD} \right] \\ &= 14.4kWh - \left[ (12.24kWh + 8.01kWh - 10.25kWh) \cdot \frac{1}{0.85} \right] \\ &= 14.4kWh - 11.76kWh \end{aligned}$$

Under the consideration of the specific battery technology mass, the battery can be downsized for 11.76kWh, i.e. 78.41kg. The values generated by the developed tool are 11.7611kWh respectively 78.0775kg.

The reduced mass results in a decreased energy consumption of 3.4% (SECA value of 0.00083kWh/m), so that in a subsequent cycle the impact to further improvement is shown.

The calculation of savings on CO<sub>2</sub> emissions follows the multiplication of reduced battery mass respectively the decreased energy consumption, so that

Reduced CO<sub>2</sub> emissions battery:

$$\begin{aligned} CO_{2-bat} &= C_{bat-reduction} \cdot \text{Emission}CO_{2-bat} = 11.76kWh \cdot 75,000 \frac{g}{kWh} \\ &= 882kg \end{aligned} \quad (54)$$

Reduced CO<sub>2</sub> emissions energy:

$$\frac{E_{cw-tn}}{E_{cw-t0}} = \frac{0.00083 kWh/m}{0.00086 kWh/m} = 3.4\% \quad (55)$$

The calculations on resource conservation and sustainability executed in the developed Excel tool are programmed in compliance with the illustrated equations (52) to (55) and show results consistent with the sample calculation outcomes, thus verifying its accuracy and reliability. The realisation within the OCSLM based Excel tool is explained in subsection 5.3.2.3.

### 5.3 OCSLM structure

The model for occasional charging station location based on its mathematical determination according to subsection 5.2.2 and its practical execution use the software Microsoft Excel in the scripting language 'Visual Basic for Applications'. The tool for OCSLM execution is subdivided into three phases such as setup, processing and result phase. The setup phase prepares the simulation execution. The processing phase operates the simulations and generates case specific results based on location-allocation modelling in reference to improved resource utilisation and sustainability as output of the result phase.

According to the structure of the used spread sheet, the operation of OCSLM is subdivided into two interfaces with different access paths such as the user interface and the operator interface (see Figure 5-8).

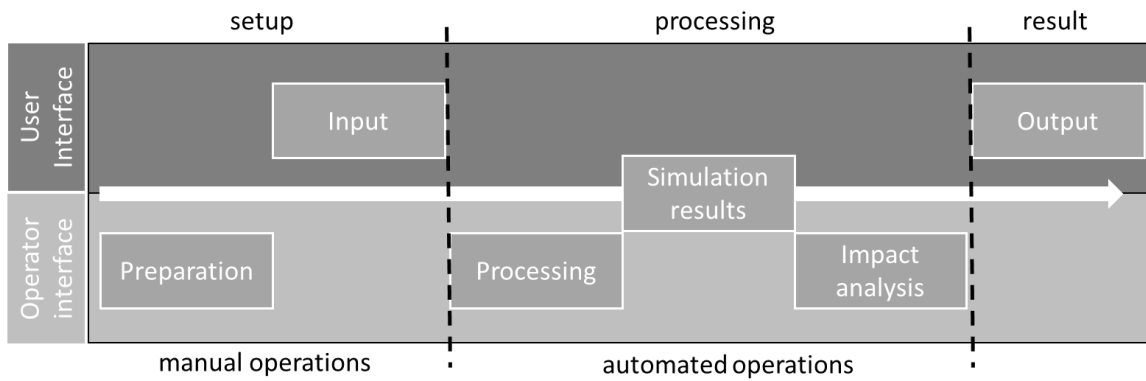


Figure 5-8: OCSLM structure

Source: Author

The user interface as realised within Excel consists of the first two data sheets named 'Input' (see Figure 5-10 [p.130]) and 'Info' (see Figure 5-11 [p.134]) according to Appendix D, whereas the underlying processing algorithms and data sheets are disposed subsequently, so that the user input is limited to general information concerning the structure and quality of shipments and energy supply information which enables the easy execution of sensitivity investigations. The operator interface accesses the mathematical, programming and fundamental set up stage of the tool in order to prepare, structure and control the simulation operations (see subsection 5.3.1.3).

The setup phase follows the data collection in reference to process data collection which targets to display the system immanent process structures and sequences. Energy data can be referred to available SECA values being independent from the specific investigation environment or can be based on dedicated energy consumption values in line with the explanations on SECA data collection and generation of section 4.2 [p.89].

The setup phase of the tool requires manual operations by the operator and the user. The operator prepares the simulations by inserting relevant process and facility data in order to attribute the simulations to the specifications of the research environment. After the initial simulation preparation by the operator the user inserts case related information or alters individual parameters. Simulation results are generated automatically and do not require additional engagement of the user. The intermediate results as generated by the simulation are fed as input to the adjacent impact analysis in order to determine the impact from charging



station implementation and occasional charging execution to the system energy balance.

For easy understanding of the OCSLM structure, the simulation execution is subdivided into six steps (macros) in order to highlight the individual functions, whilst the simulation application allows automated processing. The following section highlights more thoroughly the contents and functions of the defined simulation phases by explaining the individual worksheets.

### **5.3.1 Setup phase**

The setup phase of OCSLM operation involves the manual preparation and input of required information to the Excel tool within the operator and the user interface. Within the operator interface basic process information and data is inserted in order to prepare the application by the user, whilst the operator needs to access two different types of worksheets. These are the vehicle focused process data sheets and the auxiliary matrix sheet. The user completes this data by insertion of application alternatives in the input worksheet.

#### **5.3.1.1 Vehicle data sheet**

During the initial stage of the setup phase, process data of considered vehicles is inserted into the referred vehicle data sheet in order to base the simulation on realistic process and system behaviour (see Appendix D).

For the executed research project the required data structure has been identified in reference to the findings by Chow (1990), Mueller et al. (2013) and Mueller, Krones and Hopf (2013) and are displayed in Table 4-4 [103]. This data contains information on process routing, sequences, allocation and idle times. For the application of the OCSLM algorithm, data structure can differ from the displayed composition and granularity but needs to contain the named information.

The execution of macro #1 generates information on process idle times, number of stops as well as the vehicle individual potential and inserts it to the vehicle data sheet (see Appendix D).

#### **5.3.1.2 Auxiliary matrix**

The function of the auxiliary matrix resides in the realistic configuration and integration of the investigation environment's layout to the simulation execution. The

operator designs the auxiliary matrix in reference to the production facility's spatial arrangement by inserting walls, shelves, racks and other fixed obstacles that influence handling equipment process routing. This prohibits incorrect charging station allocation in reference to production facility conditions.

The negligence of obstacles does not necessarily result in wrong values but determines charging station allocations that are not concordant within its real application, meaning that the integration is an inevitable part of the pursued approach. As such facility conditions are considered within the auxiliary matrix by inserting negative values in the locations of walls and other obstacles in order to prevent idle time relocation across these sections (see Figure 5-9). Cells that do not represent an obstacle have the value of '0'.

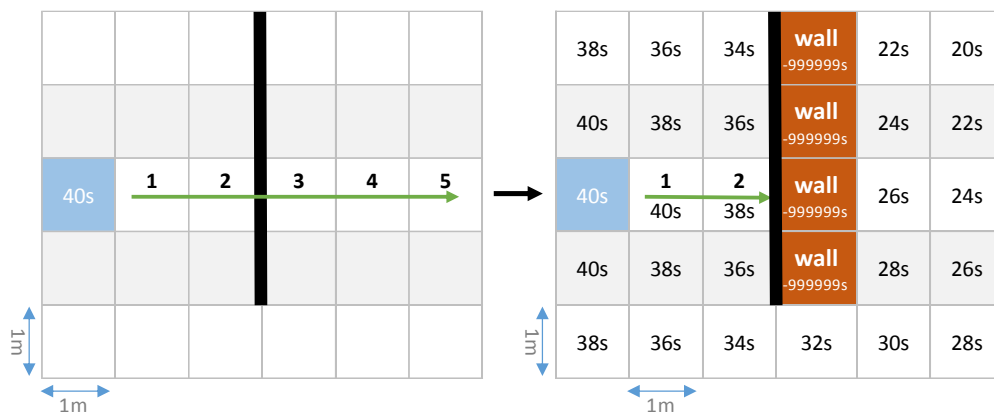


Figure 5-9: OCSLM obstacle integration a) idle time relocation b) auxiliary matrix obstacle integration  
Source: Author

The Excel tool realisation of the fundamental OCSLM equation (43) is based on a stepwise relocation of initial idle times to its neighbouring cells under the side condition (42). The values of the auxiliary matrix are added to the values of the vehicle data, so that the negative values being introduced by defined walls stop the further relocation of idle times as shown below (see also Figure 5-9-b):

$$1) E_1 = \frac{(40s \cdot 3.6kW \cdot 0.9)}{3600} = 0.036 \text{ kWh}$$

$$2) E_2 = \frac{((40s - 2 \cdot 1s) \cdot 3.6kW \cdot 0.9)}{3600} - \left( 2 \cdot 1m \cdot 0.00034 \frac{\text{kWh}}{m} \right) = 0.03352 \text{ kWh}$$

$$3) E_3 = \frac{((40s - 2 \cdot 2s) \cdot 3.6kW \cdot 0.9)}{3600} - \left( 2 \cdot 2m \cdot 0.00034 \frac{\text{kWh}}{m} \right) + \frac{(-999,999s \cdot 3.6kW \cdot 0.9)}{3600} = -899,999 \text{ kWh}$$

Subsequent idle time relocation from the initial demand spot to the fields #4, #5, etc. result in negative values, so that no further relocation is executed or is relocated around the obstacle. With increasing distance of the relocated idle time to the initial starting point, time losses as well as additional energy consumption for approaching movement decrease the amount of chargeable energy, so that  $E_n \rightarrow -899,999$  kWh. This procedure results in a non-direct-relocation of the initial idle time around the obstacle, so that the additional energy input to the battery for the fields #3, #4, #5 and all subsequent cells is assumed to be 0 kWh, respectively the decreased relocation time.

### 5.3.1.3 User interface 'Input'

On the user interface level structural process data as well as information on energy input according to Figure 5-10 can be entered and altered. A change of these values requires the repetition of the simulation process, whereas the simulation of changed values requires less computing time than an initial simulation setup and execution which can take up to 30 minutes.

	A	B	C	D	E	F	G
1	percentage of stacked units	90	%				
13	average payload	460	kg				
14			% mass				
15		50	500	kg			
16		30	150	kg			
17		15	650	kg			
18		15	450	kg			
19	SoC at $t_0$	100	%				
20	Battery energy at $t_0$	26	kWh				
21	Battery capacity	26	kWh				
22	Energy output	3,24	kW				
23	Transmission performance	3,6	kW				
24	Transmission efficiency	0,9					
25							
26							
27							
28							

Figure 5-10: User interface 'input'

Source: Author

The percentage of stacked units gives the number of loading equipment that is subject to stacking. In the example investigation 90% of the devices were stacked at an average height of 1.1m, so that in addition to the energy consumption for free lift, i.e. vertical movement over 0.1m, energy consumption for vertical movement over 1.1m was inserted in the overall process energy consumption. The number of loading devices is included within the process data according to Table 4-4 [103], so that a changing value from '0' to '1' in the column 'Loaded' represents the pickup of a loading unit.

The average payload can be inserted directly or in split up numbers in reference to the available quality of information. It has direct impact to the energy consumption in line with the integration of SECA values.

The following three specifications refer to the vehicle immanent battery system such as installed battery capacity, the assumption of the initial State of Charge at  $t_0$  which represents the day-based start of work. Given that the overarching aim of the investigations is to develop a framework in order to analyse and evaluate the potential of occasional recharging to system optimisations based on a charging station allocation modelling, these input parameters are subject to further examination subsequently to the simulation executions within the impact analysis.

The 'energy output' results from the product of 'transmission performance' and 'transmission efficiency', in reference to the installed charging system and system based charging characteristics. The selected values directly impact the amount of chargeable energy and the generation of losses along the charging processes.

### **5.3.2 Processing phase**

The processing phase of the pursued research investigation is based on the automated simulation of the input parameters. It contains the data processing by simulation execution, displaying of simulation results such as charging station allocation, total chargeable energy, additional energy efforts, etc. and the integration of simulation results to the impact analysis to investigate the impact to resource savings and sustainability.

#### 5.3.2.1 Simulation processing

The simulation is based on the execution of individual macros within the Excel tool. For easy reference individual macros and their functions are explained at this point whereas the macro design enables its automated progression.

Macro #1 – data analysis

Macro #2 – auxiliary matrix

Macro #3 – combination of matrices

Macro #4 – energy

Macro #5 – info

Macro #6 – impact to vehicles

**Macro#1 - data analysis**

After having completed the simulation setup, the first step of the data analysis calculates the process velocity as basic information for the calculation of the process energy consumption.

In the second step, the macro examines the idle times of the considered vehicle(s) while executing the process sequences. Idle times are defined as no vehicle movement in reference to the development of x- and y-coordinates, so that the subsequent occurrence of congruent values is considered as no vehicle movement, i.e. process break time. At the same time, the frequency of interrupted break time occurrence is recorded in order to determine the total time duration in one spot, as well as the number of stops that contribute to the total break time duration.

From this data three matrices (see Appendix D) are generated within the vehicle data worksheet that display

- Total net idle times in reference to its allocations
- Number of stops in reference to its allocations
- Possible chargeable energy in reference to its allocations

These matrices contain the required information in order to operate the relocation of idle times for optimised charging station allocation according to the explanations of subsection 5.2.3.2 [p.118].

Individual vehicle related information such as overall process time, accumulated volume of idle times, driving time and distance as well as average vehicle velocity are displayed in the vehicle data worksheet for individual reference.

### **Macro #2 – auxiliary matrix**

Within the execution of the second macro process related coordinates are analysed and uniformly distributed over all considered vehicles in order to design the production facility's spatial arrangement and to integrate the facility conditions according to subsection 5.3.1.2.

The auxiliary matrix is based on a meter-by-meter array of the production facility in order to assure a linear disposition of the collected data in reference to the facility layout.

**Macro #3 – combination of matrices**

This macro individually combines the generated matrices of idle times and number of stops of 'vehicle data 1' up to 'vehicle data n' and the 'auxiliary matrix' in order to combine the data in reference to a comprehensive investigation for more than one vehicle being examined (see also subsection 5.2.3.5 [p.121]). The result is the combined display of all considered data within one comprehensive matrix as the basis for further processing.

**Macro #4 – energy**

The energy macro accesses the data of the combined idle time matrix and combines it with the information about the transmission performance as given in the user interface 'input' in order to calculate the volume of net energy being theoretically chargeable to the vehicle battery.

In the next step the net chargeable energy is relocated in line with the explanations of subsection 5.2.3.2 [p.118] in order to address the demand for an endogenous covering distance.

**Macro #5 – info**

The info macro first recapitulates the hitherto generated results such as the number of considered data sets in reference to the number of vehicles being investigated, the average vehicle velocity, the overall duration of considered data sets, the total driving distance as well as the additional energy consumption for charging station approaching.

The second phase of this processing step generates the 20 charging station allocation spots of highest energy charging possibility in reference to the MCLP based OCSLM approach as shown in Figure 5-11 in extracts. In two different tables, the worksheet compares the results of the exogenous ( $S = 10\text{m}$ ) and the endogenous covering distance results. The results of the process simulation and charging station allocation are visualised within a tabular list. The top 20 generated charging allocations as displayed are subject to specific consolidation. For the executed investigations it is assumed that per each vehicle a maximum of three charging stations are determined with respect to maximal energy input (see Figure 5-11).

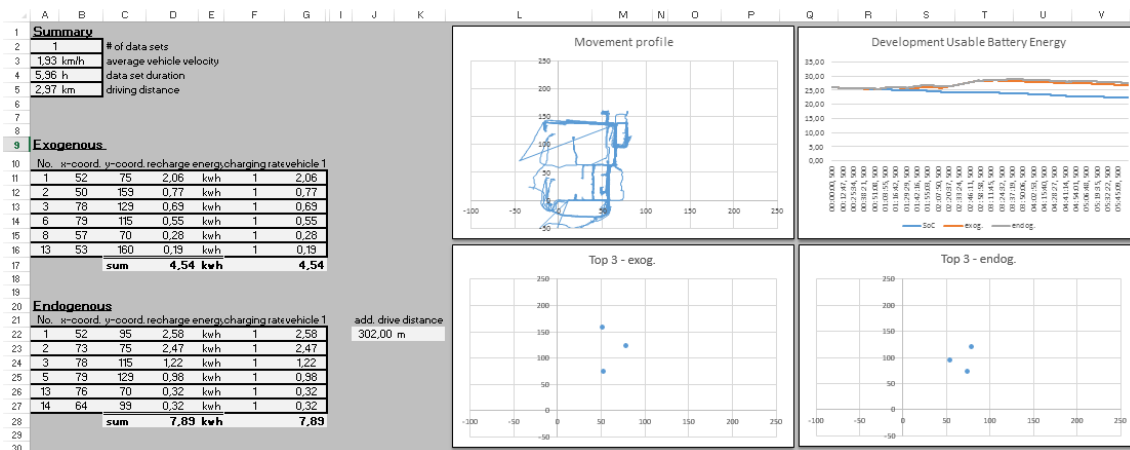


Figure 5-11: Worksheet 'info'

Source: Author

## Macro #6 – impact to vehicles

After having determined the optimised charging station allocations the impact from charging station implementation in respect to process-based occasional recharging, the impact to individual vehicle battery energy is processed by the activation of the last macro #6. The development of UBE as displayed in Figure 5-11 is calculated in respect to the individual vehicle process sequences.

The hitherto generated results are exported and displayed separately in order to summarise the intermediate simulation results that are subject of further processing in the impact analysis. These subsequent steps are explained in the following sections.

### 5.3.2.2 Simulation results

The developed OCSL model processes the input data and generates a comprehensive set of information by simulation on the investigated processes and structures in reference to the system energy balance which serve as basic information for the execution of a subsequent impact analysis.

The simulation results contain information on the process structure such as the total distance driven with relevance to energy consumption as well as information on the possible rechargeable energy which is differentiated in respect to the integration of a fixed or function based covering distance. Furthermore waste and losses with impact to the overall system efficiency are highlighted (see Table 5-4).

Dimension	Side condition	Value	Unit
covered distance		16.32	km
theoretical potential		12.69	kWh
recharge energy	$S = 10\text{m}$	4.08	kWh
	$E_{ij} > 0$	7.58	kWh
additional energy		3.50	kWh
fraction of th. potential	$S = 10\text{m}$	32.2	%
	$E_{ij} > 0$	59.7	%
top 3 potential	$E_{ij} > 0$	5.69	kWh
additional energy consumption ( $e_D$ )		0.60	kWh
non-usable potential		1.29	kWh

Table 5-4: Simulation results

Source: Author

The theoretical total potential sums up the total net idle time, which consists of process interruptions, break times and downtimes with  $v < 0.05$  m/s, that are subject to static recharging.

The rudimentary assumption for the integration of contactless power transfer systems for occasional recharging in the framework of this research project is the number of charging stations for occasional recharging being limited to a maximum of three stations per each vehicle investigated, so that the results given show the top three system allocations. Due to the flexible design of OCSLM, this ratio can be altered at any time.

Recharge energy differentiates the possible additional energy input between the alternatives of an exogenous ( $S = 10\text{m}$ ) and an endogenous ( $E_{ij} > 0$ ) covering distance. The first alternative refers to the process interruptions being within the range of ten metres from the charging station and can be used for recharging. The range of 10m was set as further basic assumption in reference to additional walking distance of equipment operators. The charging station allocation according to the  $S_{10}$  definition refers to a static determination in line with existing charging station allocation models, so that major impact emerges from the original allocation of the idle time with no idle time relocation (see Figure 5-12). By this definition only static idle times within a range of 10m are taken into account. Vehicle movement from outside the 10m range into this area, i.e. idle time relocation, is not considered.  $E_{ij} > 0$  allows recharging processes in case that the energy balance for approaching and returning to the initial break spot (see Table 5-4 'additional energy ') including the time losses for additional driving (see Table 5-4



'non-usable potential') is positive and by this increases the usable battery energy. The surplus of energy input being realised by energy efficient approaching is shown in 'additional energy'. As a combined alternative of the  $S_{10}$  and  $E_{ij}$  definitions,  $E_{ij10}$  values will be considered. This definition is a mixed approach that combines the exogenous definition of  $S_{10}$  and the endogenous definition of  $E_{ij}$ , so that an approaching process into the 10m range from outside in line with idle time relocation (see subsection 5.2.3 [p.115]) is possible under the requirement of the positive contribution to increased recharge energy. This covering distance definition has impact on the demand allocation. As such it can result in a shifting of the charging station allocation when comparing it to the  $S_{10}$  definition. Figure 5-12 illustrates the differences from the alternative covering distance definitions to the specific catchment areas, whereas  $E_{ij}$  covering distance shape is undefined and only exemplary illustrated at this point. Further impact emerges from research environment specifications such as walls or other barriers (see also Figure 5-9 [p.129]).

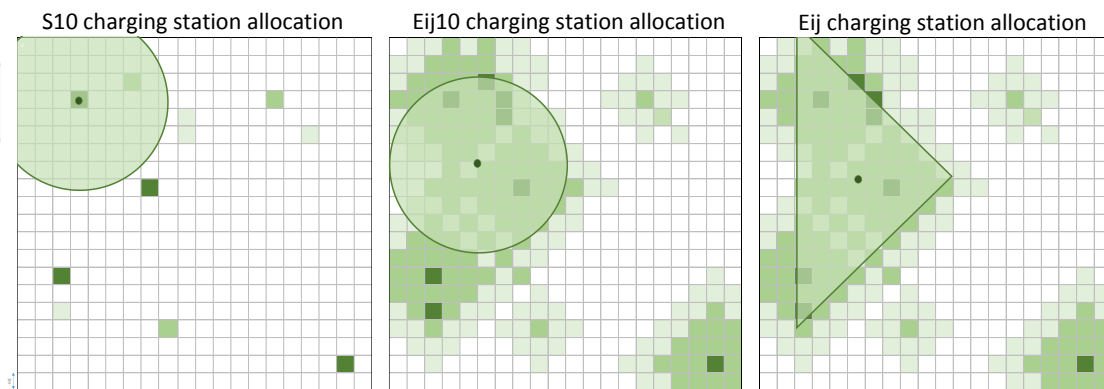


Figure 5-12: Research covering distance definitions

Source: Author

Referring back to Table 5-4 [p.135], the fraction of recharge energy to the total theoretical potential is shown in the next two lines. 'Top 3 potential' illustrates the theoretical potential that could be realised in the three locations of highest energy input as expression of the Maximum Covering Location Model. This value includes losses and waste such as 'additional energy consumption' and 'non-usable potentials' due to additional handling actions and time losses that occur in reference to the usage of occasional charging.

Furthermore, the exact allocation of charging stations is given in x- and y-coordinates according to Table 5-5. The fraction of recharge energy in reference to the

generated charging station allocations is given by 'E<sub>recharge</sub>', whereas the splitting in the last columns considers the recharge energy in reference to the investigated vehicles as expressed by 'Data1' and 'Data2'.

Top 3 charging stations S <sub>10</sub>						Top 3 charging stations E <sub>ij</sub>					
no.	x-axis	y-axis	E <sub>recharge</sub>	Data 1	Data 2	no.	x-axis	y-axis	E <sub>recharge</sub>	Data 1	Data 2
1	-1.06	23.85	3.99 kWh	3.99	0.00	1	-0.37	35.12	11.65 kWh	9.73	1.92
2	51.69	95.63	2.37 kWh	1.03	1.34	2	52.00	85.84	6.52 kWh	2.53	3.99
3	79.00	116.00	1.72 kWh	1.72	0.00	3	62.36	116.82	2.96 kWh	1.77	1.19
<b>sum</b>			<b>8.08 kWh</b>	6.74	1.34	<b>sum</b>			<b>21.14 kWh</b>	14.03	7.10

Table 5-5: OCSLM charging station allocation

Source: Author

The illustrated results of the simulation execution highlight the elements of additional usable battery energy in reference to occasional recharging in production related material handling. The generated information and interim results are evaluated within the subsequent impact analysis in reference to the potentials that emerge due to the usage of occasional recharging in order to increase efficiency and sustainability.

### 5.3.2.3 Impact analysis

In line with the explanations of subsection 5.2.4 [p.122], the cause-and-effect analysis of an occasional charging system implementation determines the changes from alternative operations to the system performance and its meaning to system design.

The impact analysis progress as illustrated in Figure 5-7 [p.123] is executed in a separate worksheet 'impact analysis' based on the intermediate simulation outcomes. The realisation of battery mass reductions initialises a self-reinforcing degradation effect from mass reduction to decreased energy consumption to mass reduction and so on (see Figure 5-7 [p.123] and subsection 5.2.4 [p.122]). The cells highlighted in red in Figure 5-13 contain basic information for pre-setting the impact analysis. The cells highlighted in yellow contain the information based on the results of the charging station allocation simulation in reference to process structures, energy consumption and recharge energy potentials (see Figure 5-13).

	A	B	C	D	E	F	G	H	I	J	K	
1												
2												
3												
4		Linde E14	Battery Capacity	V	Ah	kWh		Battery Charger	Power Rating	Volts	Amp	
5				48	440	2112				48	75	
6			Battery Weight	kg	140,8					Charging Time/day	hrs	2,5
7			Drive Distance	m	12000					Efficiency of Charger	%	91%
8			Vehicle Speed	m/sec	1,38					Number of chargers installed	pcs	3
9			Total vehicle mass	kg	2301,8					Recharge energy	kWh	8,19
10			Lifted Mass	kg	1400							
11		Battery	Additional driving distance	m	270							
12			Energy Density (Li)	kWh/kg	0,15							
13			Depth of Discharge		0,85							

Figure 5-13: Input data to impact analysis

Source: Author

In subsequent calculation cycles the simulation results are processed in order to generate the impact values from occasional recharging and the underlying system energy balance to battery design and overall CO<sub>2</sub> emissions as reference for resource conservations and increased sustainability. The results are displayed in the following output phase.

### 5.3.3 Output phase

The output of the OCSL method contains information from different sources, such as the setup phase and the processing phase. For the displaying function of the OCSLM output phase, only the information on charging station allocation and the subsequent impact from charging station allocation and implementation are highlighted at this point.

The simulation results contain the process and system optimal allocation(s) of charging stations (see subsection 5.3.2.2), the values of recharge energy, losses and waste as well as more detailed information on process energy consumption.

By the affiliation of the described steps of the impact analysis to the investigative simulations, additional information and results as the final step of the impact analysis are generated (see Figure 5-14). The results of the impact analysis within the developed Excel tool are highlighted in green and constitute additional information to the previously generated results.

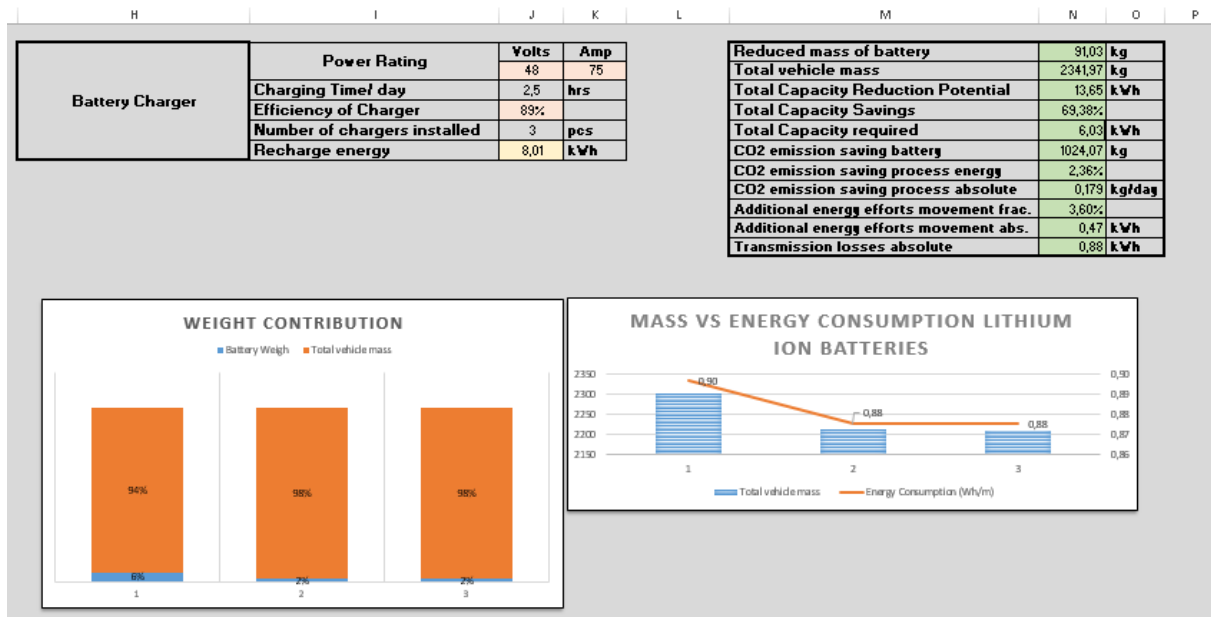


Figure 5-14: Impact analysis output

Source: Author

The 'reduced battery mass' and the values beneath it refer to the saving of battery capacity being based on additional energy input by occasional recharging. The usage of additional energy input from installed contactless power transfer charging stations enables the battery downsizing based on the process immanent potentials in reference to the self-reinforcing degradation effect. This possibility of decreased resource input fosters decreased exhaust emissions of CO<sub>2</sub> within the battery manufacturing process due to decreased battery mass<sup>1</sup>.

Due to the lowered total mass, additional energy savings can be realised within the existing process structures which is expressed in 'CO<sub>2</sub> emission saving process energy' as the representation of decreased process energy<sup>2</sup>.

As per previous explanations on OCSLM design of subsection 5.2.2 [p.108] and in reference to equation (43), the implementation of occasional charging is based on additional energy efforts for charging station approaching with contribution to the energy balance as expressed by 'additional energy efforts'. Owing to the decreased efficiency of contactless power transfer in reference to conventional plug-in charging, additional transmission losses are integrated to the comprehensive investigations.

<sup>1</sup> The emissions of CO<sub>2</sub> per kWh battery capacity of a lithium-ion battery being produced are assumed to be 75kg/kWh according to Dell'era et al. (2015)

<sup>2</sup> The emissions of CO<sub>2</sub> per kWh of electricity being consumed are assumed to be 0.564kg/kWh according to Kranke, Schmied and Schoen (2011)

## 5.4 OCSLM verification and validation

Following the presented structure of the executed research approach, the tool is subject to verification and validation in order to assure the provision of reliable and suitable information. The verification of the tool is a stepwise approach executed within the chapter specific explanations on research components, so that the overall tool verification refers to individual and chapter wise verification steps (see Figure 5-15). Tool validity is proved by the comparison of the constructed specification sheets (see section 2.6 [p.33] and 2.7 [p.50]) and the realisation of these specifications within the research design in order to assure the dedication of OCSLM to the research questions.

Verification focuses on the correctness and accuracy of a research project, so that the verification process concentrates on the setup and processing phases of the research which contains the data collection and preparation, its processing and analysis.

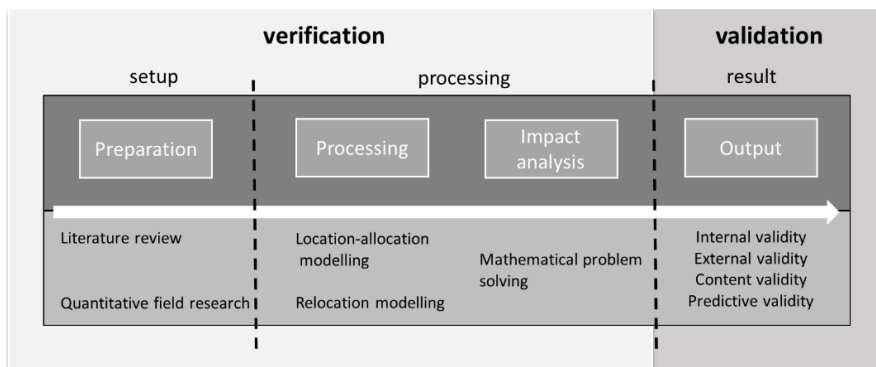


Figure 5-15: OCSLM verification and validation

Source: Author

### 5.4.1 Verification

The verification process tests the collected and generated data, as well as utilised procedures towards its accuracy and consistency. The accuracy of data, processing and calculation methods is guaranteed by several test calculations, mathematical and statistical plausibility checks, as well as research environment investigations that have been executed within the explaining chapters according to Table 5-6.

Research stage	Verification Subject	Verification mode	Place of verification	
<b>Setup Phase</b>	<b>Preparation</b>	KPI Identification	Field Research	2.3 [p.15] 2.4 [p.26]
		SECA Generation	Mathematical / Statistical Testing Plausibility Check	4.2.3 [p.94]
	Process Data Collection	Consistency / Plausibility Testing	4.2.3 [p.94]	
		Expert Review		
	<b>Processing Phase</b>	<b>Processing</b>	Location-Allocation Modelling	Field Research
			Mathematical Modelling and Testing	5.2.2 [p.108]
Relocation Modelling and simulation			Mathematical Modelling and Testing	5.2.3 [p.115]
<b>Impact Analysis</b>		Resource Saving Potential Evaluation	Mathematical Modelling and Testing	5.2.4 [p.122]
		Sustainability Calculations	Mathematical Modelling and Testing	5.2.4 [p.122]

Table 5-6: OCSLM verification

Source: Author

In reference to the verification steps as per above table, the OCSLM tool generates results corresponding to verified mathematical formulas and calculations and generates plausible results based on existing scientific knowledge, so that overall correctness and accuracy are evaluated to be verified accordingly.

#### 5.4.2 Validation

The tool validation ensures the target output generation being based on verified data and procedures, so that by the tool design and composition, the tool measures what it is supposed to measure. The target of the tool is to provide substantial processing power and to support the answering of the defined research questions. In line with the argumentation of Golafshani (2003), intermediary quality checks, as integrated in the pursued research according to the verification steps of Table 5-6, are inevitable to be implemented to research in order to assure its validity. The approach includes quality checks for the assurance of internal, external, content and predictive validity according to Cooper, Schindler and Sun (2006) in order to correctly and accurately answer the research questions (see Table 5-7).

Criteria	Validation Subject	Validation mode	Place of Validation
<b>Internal Validity</b>	Correspondence of research execution and the research target definition.	Clear structure of data collection based on existing theoretical findings and identified gaps of research.	3.3 [p.58]
			3.3 [p.58]
			5.2 [p.106]
<b>External Validity</b>	Potential of research findings for generalisations.	Design of systematic and structured research framework and model allows general applicability to any material handling environment. Application of triangulation.	2.5 [p.29]
			2.6 [p.33]
			0 [p.87]
<b>Content Validity</b>	Appropriateness of research content as applied by the used instruments.	Simulations are based on collected data, so that simulation results allow deductions to improvements in system design and sustainability.	5.4 [p.140]
			2.4 [p.26]
			3.3 [p.58]
<b>Predictive Validity</b>	Accuracy of predictions in reference to expected outcomes.	The pursued research generates predictions based on a critical literature review and tests its reliability by pilot testing and expert knowledge integration.	5.2.4 [p.122]
			5.3.3 [p.138]
			5.2 [p.106]
			5.3 [p.126]
			6 [p.144]

Table 5-7: OCSLM validation

Source: Author

The executions of Table 5-7 show the research progress intermediary quality and validity checks in order to prove OCSLM tool validity. The attainment of high validity and by this academic trustworthiness fosters the availability of 'credible and defensible results' (Johnson 1997:283), i.e. a reliable source of information of high quality research that addresses and includes all defined research questions Q1 to Q6 (see section 3.3 [p.58]).

## 5.5 Chapter summary

Chapter 5 explained and executed the research analysis by developing a dedicated Excel based tool on the application adjusted theory of Maximal Covering Location Modelling named OCSLM. The requirements to OCSLM were deduced from findings of related literature and research environment investigations. Relevant research approaches in the field of charging station allocation as reviewed in section 2.6 [p.33] were consulted for best practice approaches in order to increase the framework quality and to generate highly reliable results.

Identified requirements and specific characteristics to the research framework design as previously explained are summarised in Table 5-8. The realisation of these requirements within the executed research project was illustrated within the explanations on the analysis design and research verification. In order to answer the identified research questions the validity of research characteristics was explained, so that the composition of information in Table 5-8 illustrates the design and target fulfilment of the developed simulation and investigation approach.

Characteristics	Target Model	Realisation
Demand definition	static	✓
Demand modelling	deterministic	✓
Spatial representation	continuous	✓
Process sequencing	yes	✓
Energy consumption	accurate	✓
Energy provision	accurate	✓
Covering distance	endogenous	✓

Table 5-8: OCSLM characteristics

Source: Author

In the following chapter, the case study execution proves the practical applicability of the developed framework and, by this, exemplarily generates the desired information on system integration of occasional recharging within industrial material handling as a first reference model in this field of investigations.



# CHAPTER 6

## CASE STUDY APPLICATION

### 6.1 Introduction

The purpose of chapter 6 is to demonstrate the practical and general applicability of the developed research framework, respectively the developed model and tool for occasional charging station allocation. For that reason, a total of six related motion studies were executed and investigated which are particularised within this chapter. In order to show the general applicability of the developed framework and the OCSLM tool, single material handling vehicles with individual process sequencing, operation characteristics and production facility affiliations were investigated. Vehicles that are identical in construction with an installed nominal battery capacity of 19.68kWh and the UBE of 16.73kWh operate in different functions at individual process conditions and move in partly overlapping though individual geographic surroundings. A total of six investigated vehicles with more than 120 days of recorded process data, serve for the executed potential evaluation. A concluding comprehensive simulation on the entire fleet of vehicles was finally executed in order to show the general applicability of OCSLM as well as the impact from fleet based optimisations to individual vehicles.

As Leonard-Barton (1990) and Voss, Tsiriktsis and Frohlich (2002) comment on the beneficial aspect of a decreased number of data sets in order to focus and concentrate on the results of a high quality sample, the further executions following to section 6.2 show in-depth explanations on two individual vehicles only for increased manageability. The passages before, as well as the result comparison contain information on all fleet vehicles as these are important for the understanding of the final fleet investigation, so that detailed analyses were executed on all vehicles. More detailed explanations on the individual vehicle outcomes can be found within Appendix F.

### 6.2 Sampling and case study realisation

The definition of study samples and by this data sources being involved in the research project execution is considered to be of high importance. The decision

to consider a sample within the research process is based on the availability of resources, as well as the appropriateness and positive contribution of each sample to the target definition as the integration of all potential data sources is evaluated to be neither practical nor feasible (Marshall 1996).

In line with the purposive sampling approach that is based on the non-probabilistic researcher’s sample choice, this research is based on a selected, specifically informative and most productive sample of vehicles (Marshall 1996, Saunders et al. 2009) as shown in Figure 6-1 under random vehicle numbering. For further reference, the overall production facility layout including the assembly line allocation can be seen in Appendix G.

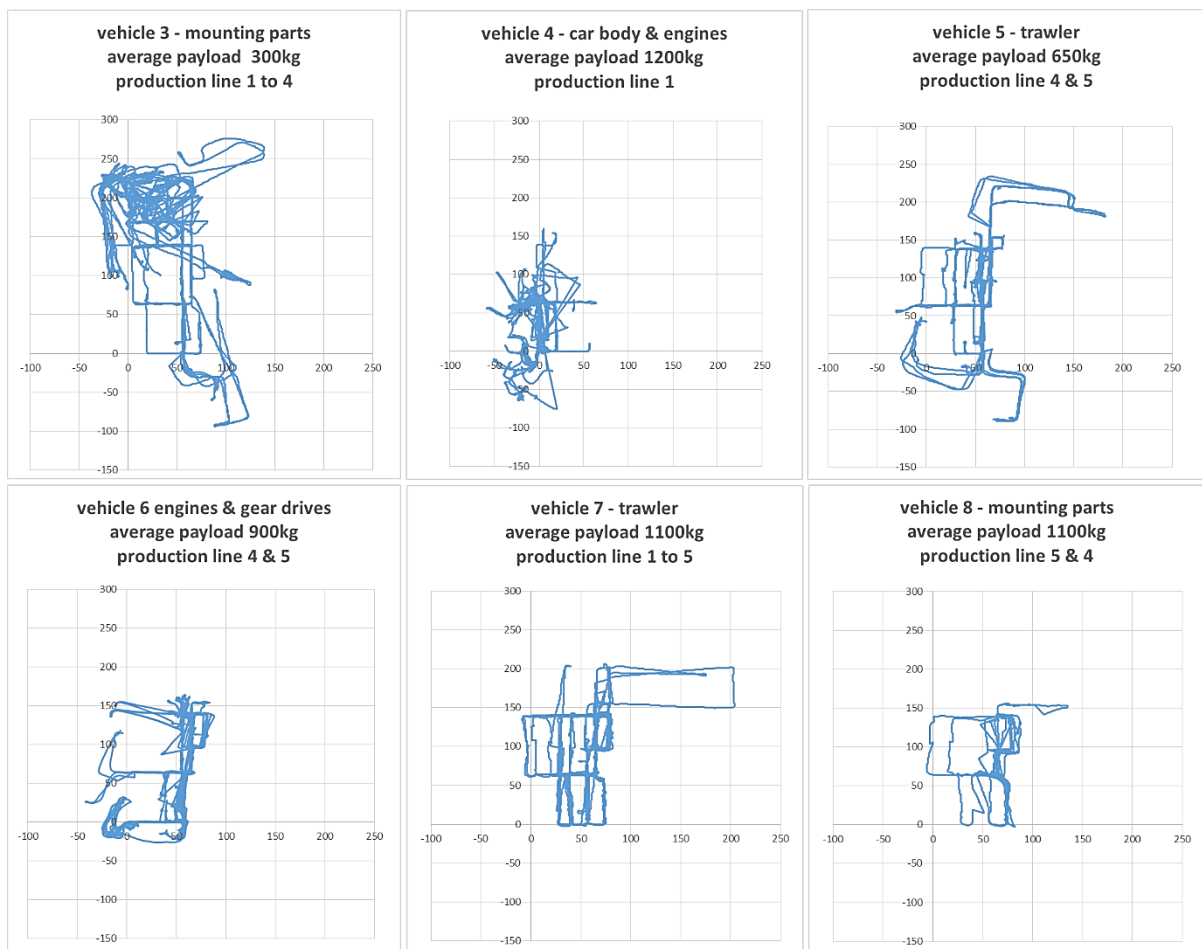


Figure 6-1: Case study movement profiles

Source: Author

Vehicle 3 provides mounting parts to the assembly lines 1 to 4 with average mass of carried loading equipment of approximately 300kg. The geographic allocation of process sequences is allocated in the back part of the assembly lines close to the evacuation zone.

The supply of car bodies and engines to production line 1 is operated by vehicle 4. Carried items rank within the high range of mass around 1,200kg per loading device. The area of operations is very much centred at the feed-in spot to line 1.

The trawler vehicle 5 provides and distributes medium-weight car-body parts with focus to the assembly lines 4 and 5 with average mass of 650kg. Its process range is distributed over a large fraction of the production facility.

Vehicle 6 supplies smaller engines and gear drives to the entry and middle sections of lines 4 and 5. The average weight is around 900kg.

The second trawler vehicle 7 distributes heavy weight load carriers of 1,100kg in average to the assembly lines 1 to 5.

Vehicle 8 focuses on the supply of line number 5 and 4 with heavy chassis mounting parts of approximately 1,100kg.

Due to the differences in reference to process sequences, process distances and speed, performance requirements due to carried payloads and process functions as well as geographic arrangement, each vehicle is investigated individually. In a final consideration, however, the fleet of considered vehicles is analysed in a combined investigation in order to address the general applicability of the mathematical optimisation model and to prove the model's qualification for complex case investigations.

The pursued research project responds to the ongoing debate on sample size appropriateness in reference to the concept of data saturation. In line with Glaser and Strauss (1967) data saturation is reached when additional samples or data does not change the results in order to answer the research question, and when redundant data patterns are observed and identified by the researcher (Bogdan and Biklen 2007). The research project on the identified samples collected 121 data sets with more than 1,252 tracked process hours as per Table 6-1.

vehicle	total hours tracked	average hours per day tracked	number of days tracked
3	116:48:30	07:47:14	15
4	114:10:19	06:20:34	18
5	302:36:34	10:05:13	30
6	277:04:39	13:11:39	21
7	276:31:51	12:01:23	23
8	116:26:55	08:19:04	14
<b>total</b>	<b>1,252:51:10</b>	<b>10:21:15</b>	<b>121</b>

Table 6-1: Case study samples  
Source: Author

Redundant patterns in data structure and analysis results have been realised in comparison of similar days in consecutive weeks of investigations, meaning that the further executions illustrate sample days only whereas the potential evaluations and results also include average numbers of the complete set of data. The case study data analysis on the samples collected illustrates the arithmetic mean value as reference value of the overall investigations as well as case related absolute minimum and maximum values as displayed for the simulation results of vehicle 8 in Figure 6-2. The arithmetic mean value can be seen to present an average shift in reference to the vehicle's performance, so that around 90% of the tracked process data lies within a deviation of +/- 8% in reference to the average case vehicles drive distance.

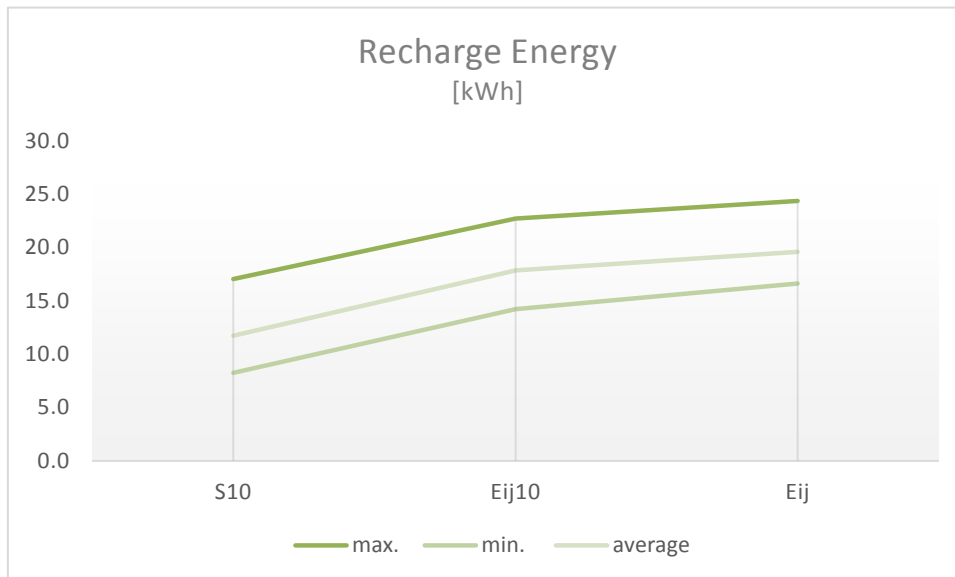


Figure 6-2: Result impact analysis vehicle 8

Source: Author

The results displayed under 'S<sub>10</sub>' are based on an exogenous covering distance  $S = 10$  metres in reference to the existing charging station allocation approaches as described in section 2.6 [p.33] (see also Giménez-Gaydou et al. 2016, Frade et al. 2011) and as explained within the analysis design in chapter 5 [p.105]. The case study results on charging station allocation exemplify the difference from endogenous to exogenous covering distance in order to highlight the benefit from accurate data which includes process sequencing.

The values under E<sub>ij10</sub> refer to the determination of charging station allocation for occasional recharging under the realisation of an exogenous-endogenous cover-

ing distance that targets to increase the recharge energy by integrating only positive potentials to charging station allocation, realised through additional charging station approaching. In order to increase comparability of the endogenous approach, the additional limitation of the covering distance of 10 metres is given. This combination of an exogenous-endogenous covering distance allows charging station approaching only under the premise of  $E_{ij} > 0$  (see subsection 5.2.2 [p.108]) and points out the positive impact of a function-based integration, and the negative impact of an exogenously determined covering distance to allocation determination, and its impact to the energy balance. The values of  $E_{ij}$  excludes the exogenous covering distance, meaning that all positive contributing charging potentials are integrated by adapting the charging station allocation in order to further increase the recharge energy.

For the determination of charging station allocation(s) and the number of charging stations to be implemented, a minimum of three charging stations being approachable by each vehicle was defined as target status, which is especially important in reference to the concluding fleet investigation. If no more than two charging stations are approachable, so that the implementation of a further charging station only serves the definition compliance, the approaching of two stations only is accepted. This definition of demand satisfaction for the fleet investigation corresponds to the charging station determination of individual vehicles.

As a fundamental assumption of the research project and a safety precaution to avoid system outage, the system adaption and improvement of the minimal battery capacity was limited by the researcher, so that battery capacity cannot be reduced to less than 20% of the initial nominal battery capacity. This restriction represents a safety standard in reference to the real technology application despite the fact that the additional UBE could theoretically allow further downsizing. This limitation restricts the extreme values of the analysis, so that for the further analysis the defined values are set as guideline.

**NOTE:**

Due to a signed non-disclosure agreement as a requirement to process data collection, neither the company and its location nor further data or facts about the company are explicitly named within this thesis. For further information on case study data, please contact the researcher through Coventry University.

### 6.3 Analysis on Vehicle 3

Vehicle 3 operates in the back part of the assembly lines 1 to 4 and supplies low weight mounting parts, so that average mass of transported load carriers ranges around 300kg. Figure 6-3 displays exemplary movement and idle time profiles, making the vehicle production facility affiliation evident. In a visual consideration increased idle time occurrence in the top left area (0/200) of the production facility becomes apparent.

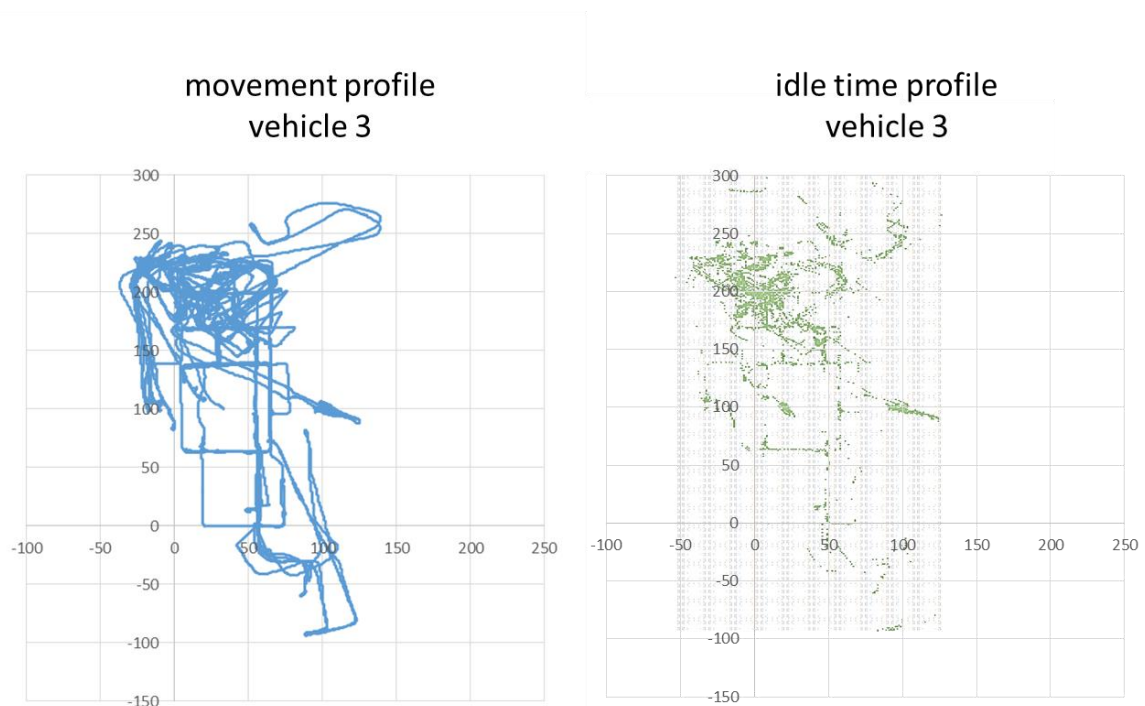


Figure 6-3: Movement (left) and idle time profile (right) vehicle 3

Source: Author

The analysis of the process sequences and process characteristics of all collected data of vehicle 3 shows an average driving distance per eight hour shift of 19,378.57 metres with an average velocity of 1.83 metres per second. Table 6-2 shows an excerpt of collected data including the shift with minimal (day 4) and maximal (day 3) driving distance.

Day	Total duration	Process Drive Distance	Average Velocity	Charging potential
	[h]	[m]	[m/s]	[kWh]
⋮				
3	8.00	21,026.31	1.52	21.08
4	8.00	14,588.06	1.59	22.78
5	8.00	18,392.45	1.73	21.23
6	8.00	19,180.54	1.87	21.76
⋮				
average	8.00	19,378.57	1.83	21.43

Table 6-2: Process data vehicle 3

Source: Author

The column ‘charging potential’ shows the theoretical proportion of idle times within the recorded process sequences in reference to the charging performance being usable for occasional recharging. As this value contains short stops of 0.5 to 1.0 seconds in different spots the usage of 100% of the theoretical potential can be omitted.

### 6.3.1 Location-allocation - vehicle 3

As a key facet of the executed research project charging station allocation is determined based on the developed model for Occasional Charging Station Location. The key components for charging station location modelling consist of process sequencing and routing, energy consumption and energy provision. As displayed for days 4 and 5 (see Table 6-3), the rechargeable energy differs from day to day. As visible, the charging station allocation differs from  $S_{10}$  to  $E_{ij10}$  to  $E_{ij}$ . In the same way the volume of rechargeable energy increases from  $S_{10}$  to  $E_{ij10}$  to  $E_{ij}$ . For the displayed sample day 4, the additional energy input from  $E_{ij10}$  to  $S_{10}$  is about 5.71 kWh which equals +45.48%. From  $E_{ij10}$  to  $E_{ij}$  this volume of energy increases for another 5.37 kWh, i.e. +29.95%, so that the total increase from  $S_{10}$  to  $E_{ij}$  is 11.08 kWh, i.e. an increase of 61.81% of recharge energy which is based on optimised charging station allocation in reference to a function based covering distance.

Day		X	Y	E <sub>recharge</sub> [kWh]	E <sub>recharge total</sub> [kWh]
4	S <sub>10</sub>	49.73	156.53	3.07	6.84
		9.33	194.89	2.73	
		64.16	100.84	1.04	
	E <sub>ij10</sub>	12.17	191.59	5.45	12.55
		50.00	195.00	3.73	
		12.00	159.00	3.38	
	E <sub>ij</sub>	14.31	167.34	8.52	17.92
		54.93	95.88	5.67	
		50.00	195.00	3.73	
5	S <sub>10</sub>	50.62	160.21	3.29	5.36
		30.00	144.00	1.04	
		38.00	175.00	1.04	
	E <sub>ij10</sub>	35.05	158.89	4.59	10.05
		48.89	174.20	3.40	
		55.64	144.90	2.07	
	E <sub>ij</sub>	39.04	167.96	11.39	13.59
		64.44	101.56	1.28	
		5.43	181.05	0.92	

Table 6-3: Charging station location vehicle 3 days 4 and 5

Source: Author

Considering the complete set of recorded data on vehicle 3, the average difference from S<sub>10</sub> to E<sub>ij10</sub> is about +35.69%; from S<sub>10</sub> to E<sub>ij</sub> +48.07%; from E<sub>ij10</sub> to E<sub>ij</sub> +19.23%.

Comparing several of the recorded days in reference to charging station allocation shows alternating allocation spots that, in a little number, correspond to each other (see Figure 6-4, left side). This highlights the importance of combined investigations in order to define charging station allocations which cover the major fraction of all operation processes and sequences. The day based illustration shows all nine suggested charging spots for S<sub>10</sub>, E<sub>ij10</sub> and E<sub>ij</sub>. As such the differences of the single location-allocation definitions becomes apparent.



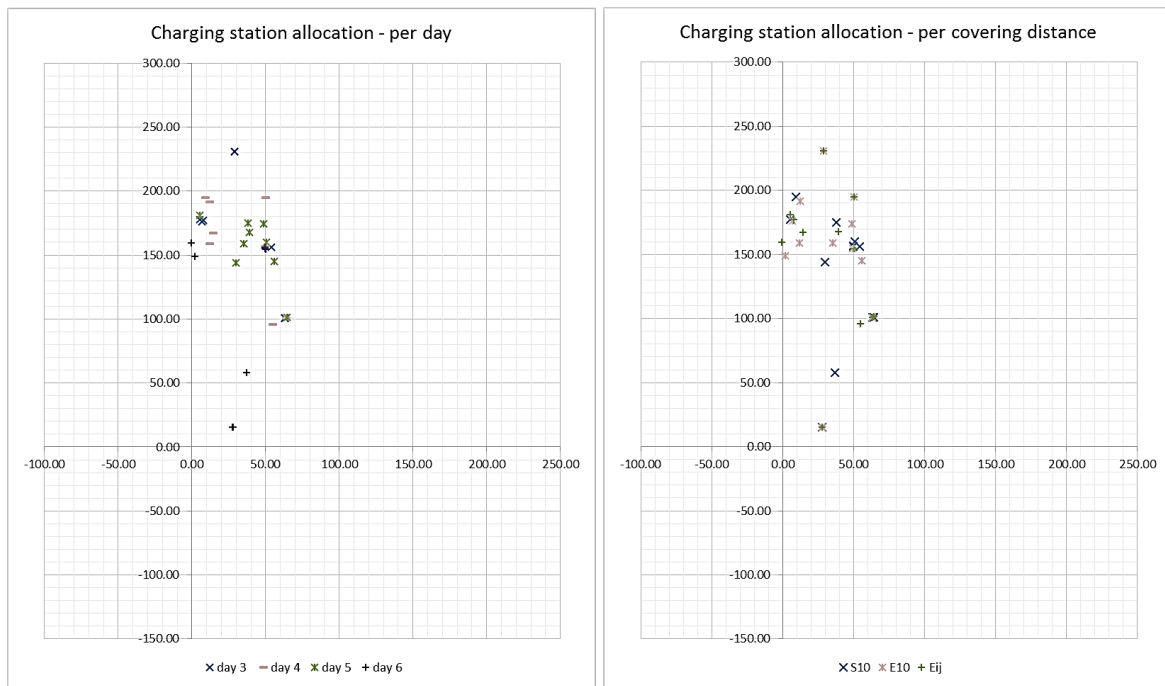


Figure 6-4: Charging station allocation vehicle 3 – per day (left); per covering distance (right)  
 Source: Author

The right part of Figure 6-4 displays the charging station allocation in reference to the definition of the covering distance. Charging stations according to the definition of  $S_{10}$  are marked by the blue crosses. In contrast to the defined charging allocations of  $E_{ij10}$  and  $E_{ij}$ , these charging station allocations coincide less (47.22%) whereas the allocations of  $E_{ij10}$  and  $E_{ij}$  more frequently allocate in the same or in close spots (80.55%). In reference to the increased energy input realised by the endogenous covering distance, this highlights the weakness of an exogenous covering distance which is numbered within the executions of the impact analysis on vehicle 3.

### 6.3.2 Simulation results - vehicle 3

In conjunction with the explanations in subsection 5.3.2.2 [p.134], simulation results include information on the total charging potential (see subsection 6.3.1), the charging potential according to the different covering distance definitions  $S_{10}$ ,  $E_{ij10}$  and  $E_{ij}$  as well as the additional drive distances involved for charging station approaching. The function based covering distance increases the required additional drive distance due to the shifting of charging stations to optimised allocations (see Table 6-4).

Day	Charging potential	Static charging potential $S_{10}$	Practical charging potential $E_{ij10}$	Additional drive distance $E_{ij10}$	Practical charging potential $E_{ij}$	Additional drive distance $E_{ij}$
	[kWh]	[kWh]	[kWh]	[m]	[kWh]	[m]
⋮						
3	21.08	11.38	12.77	372.31	13.85	541.54
4	22.78	6.84	12.55	416.21	17.92	901.78
5	21.23	5.36	10.05	158.77	13.59	344.00
6	21.76	6.94	17.10	234.98	18.38	402.82
⋮						
average	21.43	7.93	12.33	248.30	15.27	579.07

Table 6-4: Simulation results vehicle 3

Source: Author

The displayed simulation results show the additional drive distance being required in order to increase the vehicle’s UBE. While the increase of UBE from  $E_{ij10}$  to  $E_{ij}$  accounts for +23.84% in average, the additional drive distance almost doubles, so that the impact from this additional energy consumption to the overall system energy balance has to be considered within the impact analysis. Referring to an endogenous covering distance increases the fraction of the theoretical charging potential being usable for recharging from 37.00% to 71.25%.

Figure 6-5 sums up the maximum and minimum values of the case study analysis. The ‘max.’ values refer to the greatest possible recharge energy of all tracked days being realised in reference to the different covering distance definitions, while the ‘min’ values refer to the contrary case of least energy being rechargeable. The additional drive distances show no mutual dependency, whereas the increase of rechargeable energy from  $S_{10}$  to  $E_{ij}$  shows an almost linear increase

of all values with the difference from minimum to maximum values (for  $S_{10} = 6.02\text{kWh}$ ; for  $E_{ij} = 4.79\text{kWh}$ ) remaining in a comparable range.

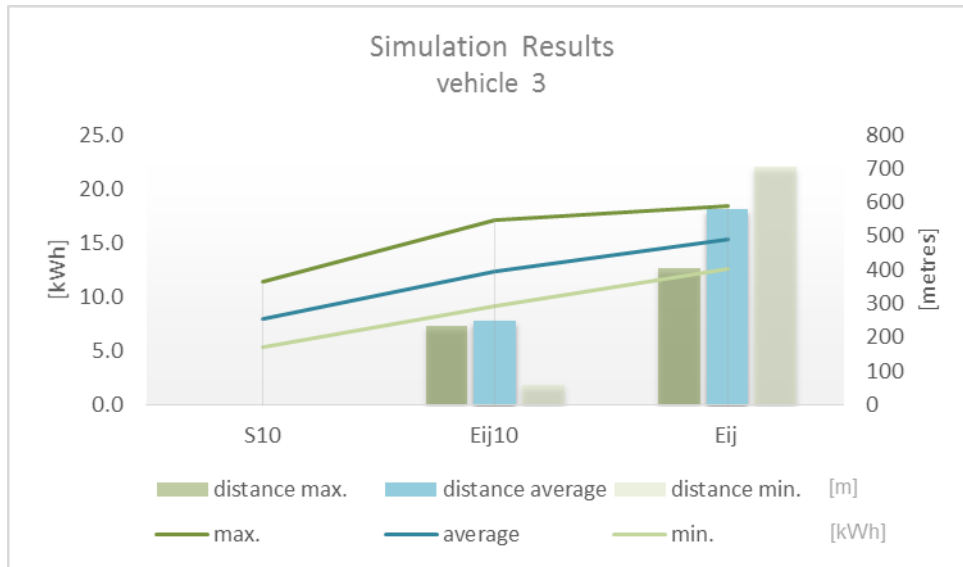


Figure 6-5: Simulation results vehicle 3

Source: Author

### 6.3.3 Impact analysis – vehicle 3

The impact analysis puts the simulation results in the context of its application environment in order to investigate the influence from different charging station location definitions to additional energy input. The meaning of additional UBE to system design, resource saving and sustainability is examined based on the displayed intermediate results.

In addition to the results on charging station allocation and the meaning to increased recharge energy, the results of Table 6-5 show the average reduction potential of battery capacity for  $S_{10}$  being lower than the defined maximum of  $15.74\text{kWh}$  as per minimum battery capacity restriction (see section 6.2). The average battery capacity required in order to assure a constant equipment availability is identified as  $6.76\text{kWh}$  of nominal capacity which is  $65.56\%$  lower than the initial battery capacity. Due to the decrease of battery mass, average process energy consumption can be lowered for  $3.22\%$ , whereas the maximum process energy savings account for  $4.37\%$ .

Day	Battery capacity reduction	Required capacity	CO2 Reduction battery	Reduction process energy	CO2 reduction process	Additional energy efforts movement	Additional energy efforts movement	Transmission losses
$S_{10}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
3	15.74	3.94	1,180.80	4.37	0.377	-	-	1.25
4	15.74	3.94	1,180.80	4.37	0.262	-	-	0.75
5	10.71	8.97	803.40	2.92	0.22	-	-	0.59
6	11.92	7.76	893.73	2.92	0.229	-	-	0.76
⋮								
average	12.92	6.76	968.75	3.22	0.232	-	-	0.87

$E_{ij10}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
3	15.74	3.94	1,180.80	4.37	0.377	1.77	0.26	1.4
4	15.74	3.94	1,180.80	4.37	0.262	2.85	0.29	1.38
5	15.74	3.94	1,180.80	4.37	0.33	0.86	0.11	1.11
6	15.74	3.94	1,180.80	4.37	0.344	1.23	0.16	1.88
⋮								
average	15.74	3.94	1,180.80	4.37	0.348	1.28	0.17	1.36

$E_{ij}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
3	15.74	3.94	1,180.80	4.37	0.377	2.58	1.52	1.52
4	15.74	3.94	1,180.80	4.37	0.262	6.18	0.63	1.97
5	15.74	3.94	1,180.80	4.37	0.33	1.87	0.24	1.49
6	15.74	3.94	1,180.80	4.37	0.344	2.1	0.28	2.02
⋮								
average	15.74	3.94	1,180.80	4.37	0.296	4.03	0.44	1.73

Table 6-5: Impact analysis results vehicle 3  
 Source: Author

Examining the values of  $E_{ij10}$  and  $E_{ij}$  in reference to the increase of recharging energy for +48.06% from  $S_{10}$  to  $E_{ij}$ , the results show that the additional energy input enables the battery downsizing for the maximum value of 15.74kWh, i.e. to the minimum required battery capacity of 3.94kWh. Investigating the critical value at which no more downsizing of the vehicle’s battery is possible, an additional energy input of more than 10.13kWh entails no more battery downsizing in respect to the defined limitation.

For battery and system downsizing, the minimal, i.e. the lowest, volume of energy being rechargeable requires special attention as this value results in system standstill in days of low idle time availability. The minimum values are displayed in Figure 6-6.

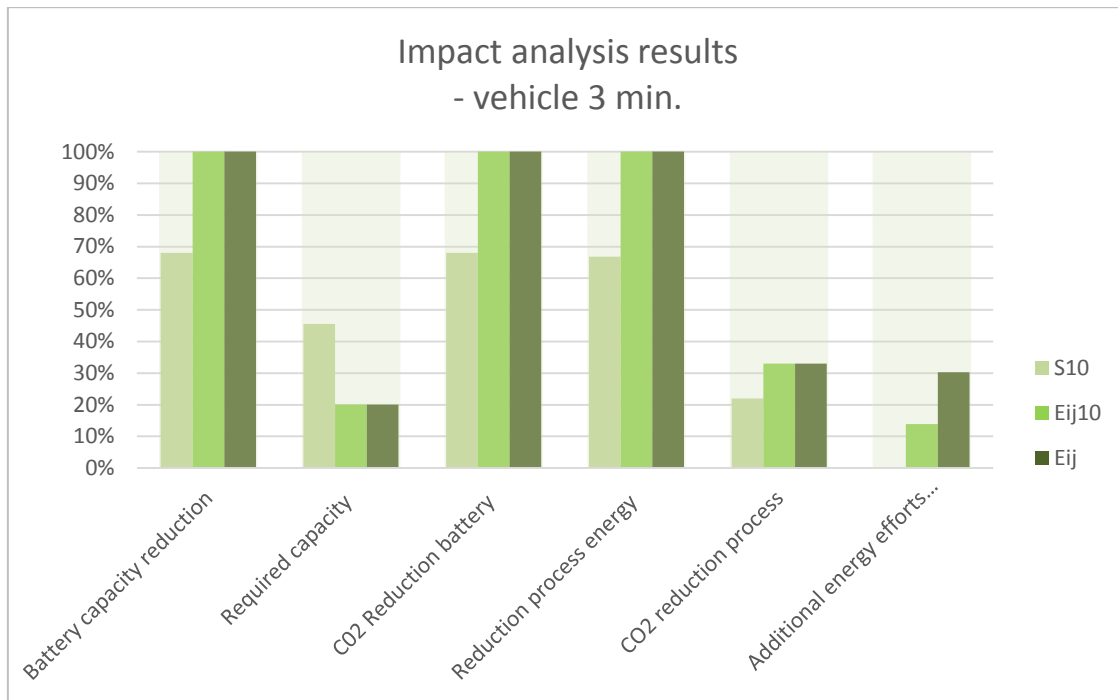


Figure 6-6: Impact analysis results minimum recharging vehicle 3

Source: Author

The results indicate, that due to the impact of low recharging energy shifts, battery capacity cannot be downsized lower than 8.97kWh for the charging stations being implemented based on a static, exogenously defined covering distance. The reference to an endogenous, function-based covering distance improves charging station allocation, meaning that the maximum downsizing potential can be used even at shifts of low recharge potential.

The reduction of CO<sub>2</sub> emission corresponds directly to the reduced vehicle/battery mass, so that increased weight savings result in decreased CO<sub>2</sub> emission. Due to increased efforts for charging station approaching, additional energy is consumed for planar vehicle movement for E<sub>ij10</sub> and E<sub>ij</sub> charging station definition. In contrast to the values of Figure 6-6 of 12% respectively 30% of the maximum additional energy consumption measured, additional energy consumption in reference to overall energy consumption accounts for 1.28% respectively 4.03% (see Table 6-5).

## 6.4 Analysis on Vehicle 4

The examination of vehicle 4 (see Figure 6-7) shows its facility affiliation in the feed-in area of assembly line 1, where car bodies and palletised engines with average mass of 1,200kg are supplied. Major driving routes and break time allocations are displayed in the area around (0/70).

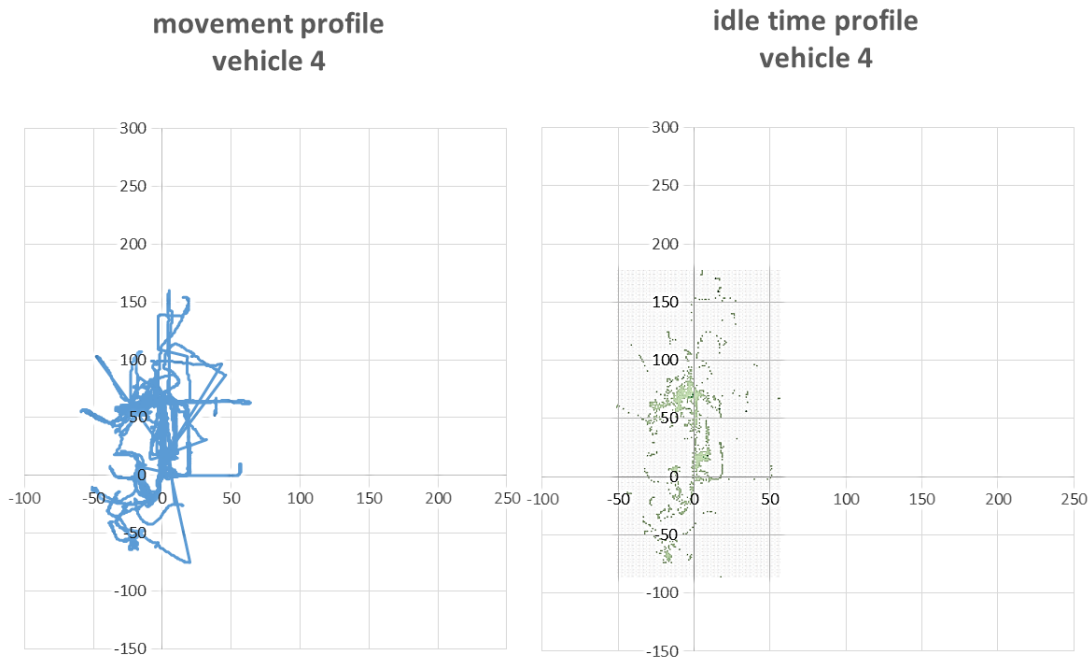


Figure 6-7: Movement (left) and idle time profile (right) vehicle 4

Source: Author

Process investigations show average drive distances around 15,601m at average velocity of 1.77m/s according to Table 6-6. Day 12 denotes the minimal and day 9 the maximum system stress in reference to process distance and velocity as indicators for process energy consumption.

Day	Total duration	Process Drive Distance	Average Velocity	Charging potential
	[h]	[m]	[m/s]	[kWh]
⋮				
<b>2</b>	8.00	14,785.01	1.53	22.77
<b>7</b>	8.00	14,926.02	1.78	22.78
<b>9</b>	8.00	15,865.23	1.91	22.80
<b>12</b>	8.00	12,645.40	1.59	24.05
⋮				
<b>average</b>	8.00	15,601.60	1.77	23.23

Table 6-6: Process data vehicle 4  
 Source: Author

**6.4.1 Location-allocation – vehicle 4**

Referring to the left part of Figure 6-8 the arrangement of the most beneficial charging station allocations shows a similar distribution over the diagrammed days within differentiated areas. Day 7 shows the highest deviation from the remaining days within this consideration.

In a different case study examination of charging station allocations which is based on the covering distances, the influence from the two remote deviating spots of Day 7 becomes apparent. While the charging spot in (143.88/229.88) contributes with 2.59kWh to the overall recharge energy within the  $S_{10}$  consideration, this spot is not considered within the charging station allocation definition of  $E_{ij10}$  and  $E_{ij}$  as the rechargeable energy is lower than in the remaining spots due to higher density of demand spots and therefore recharge energy. In contrast, the charging station allocation in (38/230) positively contributes to the energy balance by the consideration of  $E_{ij10}$  and  $E_{ij}$  definition in combination with charging station approaching, meaning that it is further considered as a charging spot.

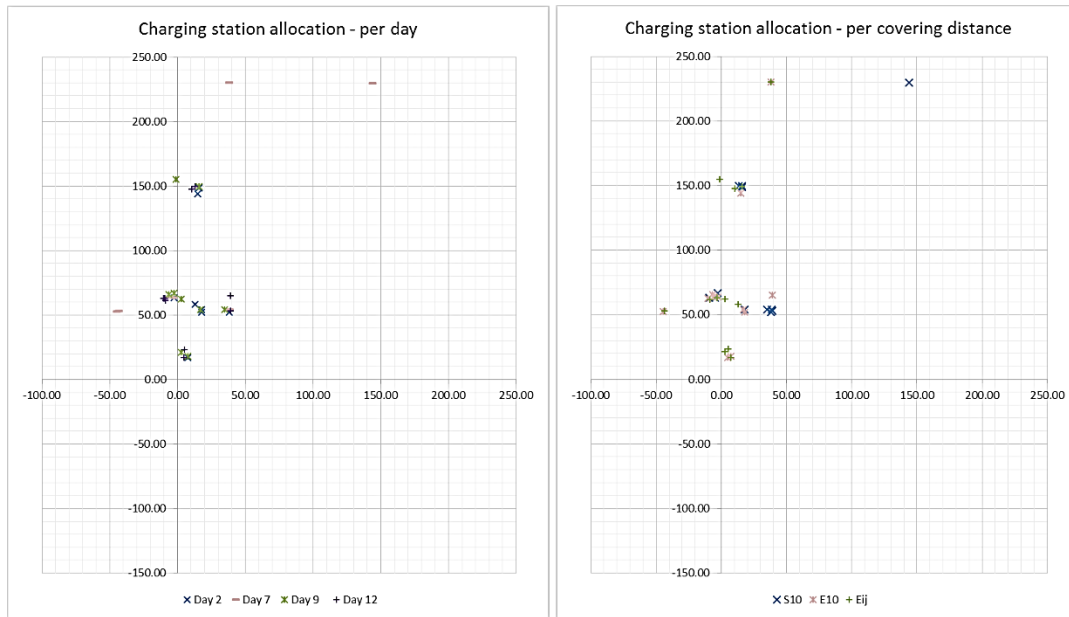


Figure 6-8: Charging station allocation vehicle 4 - per day (left); per covering distance (right)

Source: Author

Considering the total number of recorded days, the minimal recharge energy of  $S_{10}$  is 7.24kWh, while  $E_{ij10}$  allows recharging of 11.90kWh and  $E_{ij}$  14.79kWh (see also Table 6-7). In reference to the average figures, the increase of UBE from  $S_{10}$  to  $E_{ij}$  is about +42.87%, while  $E_{ij10}$  is at +33.09% above the value of the conventional charging station allocation of  $S_{10}$ .

#### 6.4.2 Simulation results – vehicle 4

The vehicle simulation results according to Table 6-7 show an increasing recharge energy as per previous explanations. In reference to the different definitions of covering distance, also the required additional drive distance increases in average about 32.81%. The fraction of rechargeable energy based on the theoretical charging potential increases from 42.34% for  $S_{10}$ , to 63.28% for  $E_{ij10}$  and 74.11% for  $E_{ij}$ .



Day	Charging potential [kWh]	Static charging potential $S_{10}$ [kWh]	Practical charging potential $E_{ij10}$ [kWh]	Additional drive distance $E_{ij10}$ [m]	Practical charging potential $E_{ij}$ [kWh]	Additional drive distance $E_{ij}$ [m]
⋮						
2	22.77	7.24	11.90	95.22	15.68	190.43
7	22.78	8.78	16.18	581.54	18.19	756.00
9	22.80	8.64	14.95	875.20	19.95	1,273.02
12	24.05	10.47	13.28	382.22	14.79	509.63
⋮						
average	23.23	9.83	14.70	445.24	17.21	662.63

Table 6-7: Simulation results vehicle 4

Source: Author

The development of the ‘max.’, ‘min.’ and ‘average’ values in reference to the rechargeable energy as displayed in Figure 6-9 illustrate the almost linear increase in values from  $S_{10}$  to  $E_{ij}$ . The growth of  $E_{ij10}$  and  $E_{ij}$  proceeds in similar proportions, so that also the deviation in values remains constant over the investigation.

The additional drive distance for the ‘max.’ and ‘min.’ consideration from  $E_{ij10}$  to  $E_{ij}$  increases about 6.5 times, resulting in an increased energy consumption of +2.72% respectively +7.05% in reference to  $S_{10}$ .

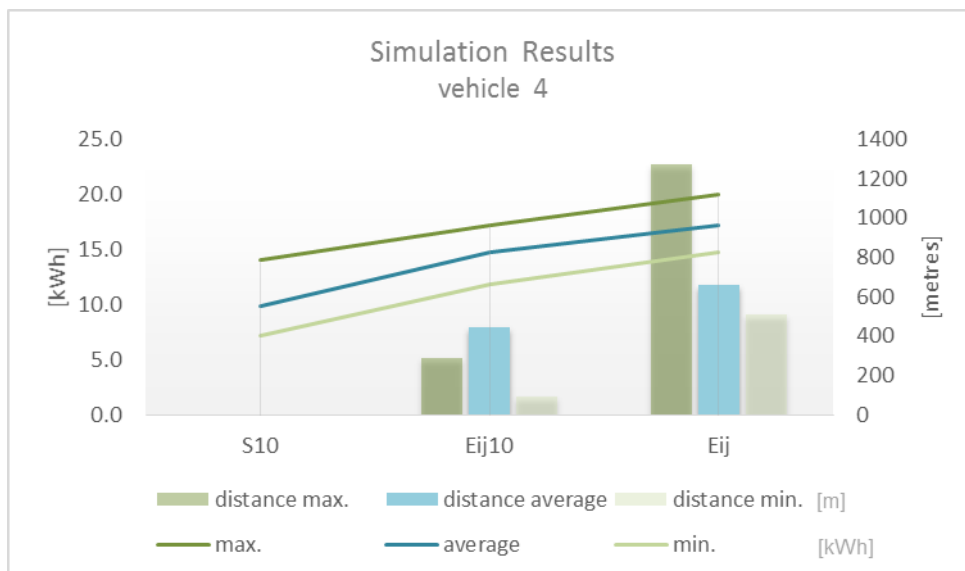


Figure 6-9: Simulation results vehicle 4

Source: Author

### 6.4.3 Impact analysis – vehicle 4

Completing the investigations by the evaluation of the impact analysis shows that charging station integration based on the  $S_{10}$  definition enables the maximal battery capacity reduction for the sample day 12. On average, battery capacity can be downsized for 13.43kWh, i.e. 85.32% of the defined maximum potential. The average required battery capacity is at 6.25kWh. In contrast to this and shown in Figure 6-10, in its application battery capacity can be downsized for the  $S_{10}$  definition for 80% only, as the minimal recharge energy of day 2 limits the downsizing to 7.08kWh. This reduction of battery mass results in a decreased process energy consumption of 2.31%, whereas the maximum process energy savings based on a 100% battery downsizing accounts for 4.62%. Maximal reduction can be achieved by the charging station allocation optimisation according to OCSLM which is highlighted by the average values of  $E_{ij10}$  and  $E_{ij}$ .

Day	Battery capacity reduction	Required capacity	CO2 Reduction battery	Reduction process energy	CO2 reduction process	Additional energy efforts movement	Additional energy efforts movement	Transmission losses
$S_{10}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
2	12.60	7.08	945.08	2.31	0.177	-	-	0.80
7	14.26	5.42	1069.81	2.31	0.178	-	-	0.97
9	13.11	6.57	983.15	2.31	0.190	-	-	0.95
12	15.74	3.94	1180.80	4.62	0.302	-	-	1.15
⋮								
average	13.43	6.25	1,007.45	2.31	0.178			0.89

$E_{ij10}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
2	15.74	3.94	1,180.80	4.62	0.354	0.64	0.08	1.31
7	15.74	3.94	1,180.80	4.62	0.357	3.90	0.54	1.78
9	15.74	3.94	1,180.80	4.62	0.379	5.52	0.77	1.64
12	15.74	3.94	1,180.80	4.62	0.302	3.02	0.33	1.46
⋮								
average	15.74	3.94	1,180.80	4.62	0.356	2.27	0.31	1.55

$E_{ij}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
2	15.74	3.94	1,180.80	4.62	0.354	1.3	0.17	1.72
7	15.74	3.94	1,180.80	4.62	0.357	5.06	0.66	2.00
9	15.74	3.94	1,180.80	4.62	0.379	8.02	1.11	2.19
12	15.74	3.94	1,180.80	4.62	0.302	4.03	0.45	1.63
⋮								
average	15.74	3.94	1,180.80	4.62	0.356	3.18	0.42	1.86

Table 6-8: Impact analysis results vehicle 4

Source: Author

Simulation analysis results show the minimum energy input of 7.24kWh for  $S_{10}$ ; 11.90kWh for  $E_{ij10}$  and 14.79kWh for  $E_{ij}$  (see Table 6-7 [p.160]). The investigations confirm that the maximal downsizing potential is limited at an average value of 9.67kWh, meaning that above this value no more battery downsizing is possible. This limitation highlights that for the design of vehicle 4, charging station allocation according to  $E_{ij10}$  definition is sufficient in order to achieve the maximum potential for battery downsizing, so that additional energy efforts due to increased approaching processes in line with  $E_{ij}$  can be avoided.

The illustration of Figure 6-10 shows the maximal potential exhaustion for the minimum values within the  $E_{ij10}$  and  $E_{ij}$  consideration. In reference to the maximal CO<sub>2</sub> reduction potentials within the process operations, the minimum days reach approximately 90% of the maximal saving potentials, whereas the additional energy efforts for movement highlight the preference to the  $E_{ij10}$  definition in this examination due to lowered energy efforts that result in the same ratio of resource saving at increased sustainability parameters.

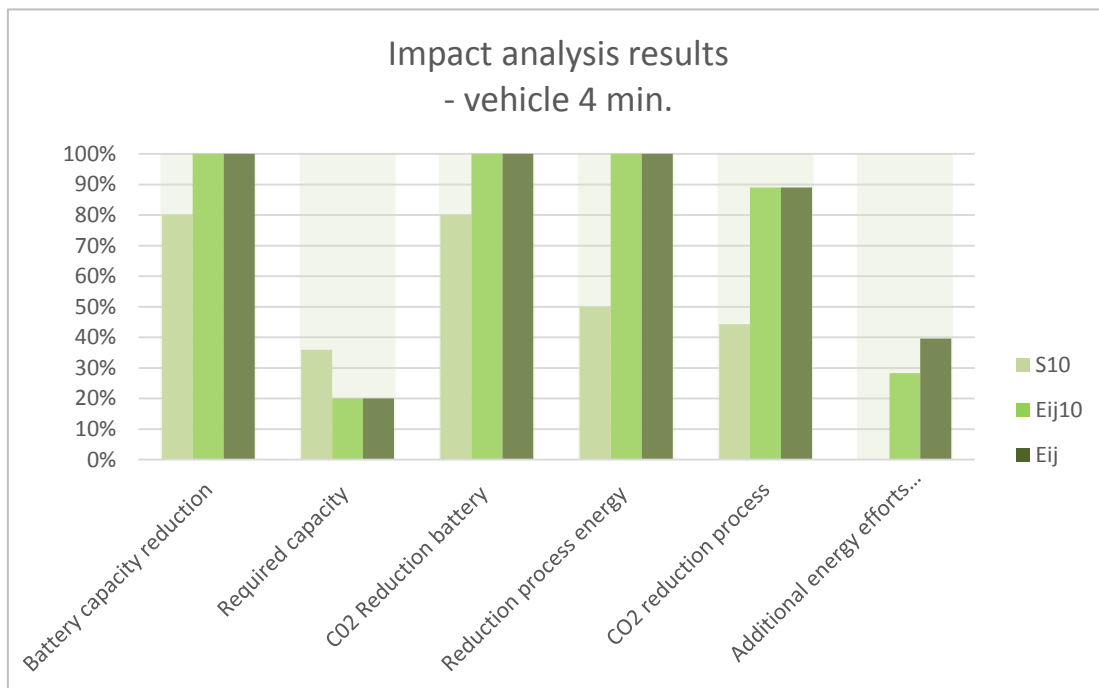


Figure 6-10: Impact analysis results minimum recharging vehicle 4

Source: Author

## 6.5 Fleet investigation

The fleet investigation is a comprehensive case investigation that integrates and combines the previous case study examples in a summarised examination. The fleet of vehicles 3 to 8 are investigated in an overall fleet consideration in order to highlight the difference from isolated to combined investigations. It also seeks to prove the applicability of OCSLM to a more complex research design.

Process characteristics as depicted in Table 6-9 such as sequences, routes, distances, processing times and speed as well as the resulting charging potentials correspond to the previously used data in order to enable the direct comparison of individual to combined investigations.

Day	Total duration	Process Drive Distance	Average Velocity	Charging potential
	[h]	[m]	[m/s]	[kWh]
⋮				
3 / 4	8.00	14,588.06	1.59	22.78
3 / 5	8.00	18,392.45	1.73	21.23
⋮				
4 / 2	8.00	14,785.01	1.53	22.77
4 / 7	8.00	14,926.02	1.78	22.78
⋮				
5 / 28	8.00	16,443.43	1.81	20.80
5 / 46	8.00	18,402.57	1.79	18.36
⋮				
6 / 20	8.00	16,550.78	1.62	22.44
6 / 30	8.00	17,731.39	1.54	17.16
⋮				
7 / 29	8.00	9,367.35	2.00	19.03
7 / 30	8.00	10,671.33	1.85	24.47
⋮				
8 / 3	8.00	10,472.36	1.65	24.93
8 / 6	8.00	9,064.93	1.46	25.46
⋮				
<b>average</b>	<b>8</b>	<b>14,282.97</b>	<b>1.70</b>	<b>21.85</b>

Table 6-9: Process data fleet investigation

Source: Author

### 6.5.1 Location-allocation – fleet

The distribution of the charging stations as displayed in Figure 6-11 displays an evenly distribution over the entire production facility, whereas the distribution of  $E_{ij10}$  and  $E_{ij}$  majorly correspond and the  $S_{10}$  definitions includes charging station allocation in more remote locations.

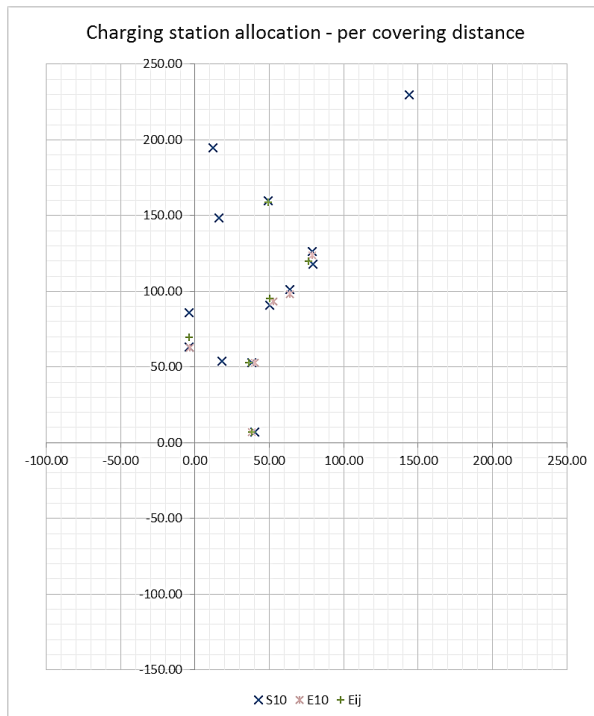


Figure 6-11: Charging station allocation per covering distance fleet  
Source: Author

The arrangement of charging allocations being implemented within the  $S_{10}$  consideration (blue crosses) is based on an increased number of charging stations of a total of 13 stations, whereas the definition of  $E_{ij10}$  and  $E_{ij}$  refers to a total of six stations only. This proportion emerges due to the pre-defined assumption of three charging stations being approachable by each vehicle whereas the overall target consists in the maximisation of recharge energy in reference to the entire fleet. Table 6-10 illustrates the charging rate of charging stations in reference to individual vehicles in order to address the demand of coverage. The cells highlighted in green show the vehicles’ recharging at the respected charging stations. The cells that are highlighted in green and show a charging energy of 0.00kWh are characterised by low charging times, so that the energy input appears after the second decimal place only. The displayed consideration reveals the increased coverage by the endogenous covering distance definition, so that less charging stations can be used while increasing the overall recharge energy from

38.06kWh for  $S_{10}$  on 13 charging stations to 98.92kWh for  $E_{ij10}$  and 113.20kWh for  $E_{ij}$  on six charging stations each.

The impact to the energy balance of individual participating vehicles is subject to the subsequent investigations on simulation and impact analysis results.

Day	X	Y	$E_{recharge}$ [kWh]	Vehicle	3	3	4	4	5	5	6	6	7	7	8	8
				Day	4	5	2	7	28	46	20	30	29	30	3	6
$S_{10}$	40.00	7.00	6.15		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.14	0.00	0.00	0.00
	79.52	117.84	6.38		0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.70	0.00	0.00	2.40	1.28
	78.76	126.52	4.21		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	1.70	2.50
	50.00	91.00	2.38		0.00	0.00	0.00	0.00	2.37	0.00	0.00	0.01	0.00	0.00	0.00	0.00
	144.00	230.00	2.22		0.00	0.00	0.00	2.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	38.00	53.00	2.14		0.00	0.00	0.00	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	49.00	160.00	2.03		0.00	2.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-4.00	63.00	1.92		0.00	0.00	0.50	1.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-4.00	86.00	3.71		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.86	1.85	0.00	0.00
	16.10	148.48	3.04		0.00	0.00	3.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	18.00	54.00	1.54		0.00	0.00	1.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	64.00	101.00	1.26		0.85	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	12.00	195.00	1.07		1.05	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$E_{ij10}$	78.85	123.67	54.14		0.02	0.00	0.00	0.00	0.00	0.00	0.82	7.29	4.02	5.03	15.06	14.82
	40.00	53.00	10.23		0.47	0.00	0.00	2.11	0.00	0.55	2.68	0.00	5.81	0.00	0.00	0.26
	38.00	7.00	8.98		0.00	0.00	1.87	1.93	0.00	0.00	0.00	0.02	6.13	0.14	0.00	0.00
	-3.40	62.60	11.22		0.00	0.00	2.60	3.62	0.00	0.04	0.00	0.00	0.64	2.37	1.41	0.00
	52.82	93.39	9.15		1.87	0.00	0.00	0.00	7.40	0.59	1.10	0.00	0.63	0.06	0.00	0.24
	64.00	98.00	5.20		1.95	0.51	0.00	0.00	0.42	0.26	0.01	0.04	0.55	0.40	1.61	0.21
$E_{ij30}$	76.35	119.64	63.02		1.97	0.51	0.00	0.00	3.26	0.28	1.75	7.33	4.57	5.50	16.67	15.27
	36.13	52.68	15.10		0.47	0.00	2.03	2.11	0.54	0.55	2.68	0.00	5.83	0.17	0.02	0.31
	38.00	7.00	8.98		0.00	0.00	1.87	1.93	0.00	0.00	0.00	0.02	6.13	0.14	0.00	0.00
	-3.85	69.48	15.63		0.00	0.00	2.60	3.62	0.00	0.04	0.00	0.00	2.50	4.93	1.41	0.00
	50.00	95.00	5.47		1.87	0.00	0.00	0.00	4.57	0.57	0.18	0.00	0.63	0.00	0.00	0.00
	49.00	159.00	5.01		2.93	2.02	0.00	0.00	0.14	0.00	0.00	0.01	0.00	0.00	0.00	0.00

Table 6-10: Charging station utilisation per vehicle and covering distance  
Source: Author

### 6.5.2 Simulation results – fleet

The fleet investigation simulation results (see Table 6-11) indicate a lower level of recharge energy for all examined covering distances and vehicles in reference to the individual investigations. Referring to the energy balance of day 2 for vehicle 4 depicts decreasing values from  $S_{10}$  to  $E_{ij10}$ . This can be explained by the larger number of charging stations of  $S_{10}$ , the existent and corresponding limitation of  $E_{ij10}$  as exogenous-endogenous covering radius of 10m and the target of recharge energy maximisation for the overall fleet, meaning that the optimisation decreases charging values for individual vehicles. This argumentation is supported by the increased overall energy input that shows increasing values from  $S_{10}$  to  $E_{ij}$ .

The consideration of rough average numbers shows the usage of 14.50% of the average theoretical potential for  $S_{10}$ ; 37.21% for  $E_{ij10}$  and 41.92% for  $E_{ij}$  and by

this a lower but corresponding percentage distribution in reference to the individual case investigations. Furthermore Table 6-11 illustrates non-coverage of S<sub>10</sub> for individual days of vehicle 5 and 6, as well as low charging values for the OCSLM considerations. The impact of these low recharge energy cases is further investigated within the impact analysis.

Day	Charging potential [kWh]	Static charging potential S <sub>10</sub> [kWh]	Practical charging potential E <sub>ij10</sub> [kWh]	Additional drive distance [m]	Practical charging potential E <sub>ij30</sub> [kWh]	Additional drive distance [m]
⋮						
3 / 4	22.78	1.89	4.31	220.70	7.23	370.70
3 / 5	21.23	2.46	0.51	26.30	2.53	129.20
⋮						
4 / 2	22.77	5.08	4.47	71.40	6.50	103.90
4 / 7	22.78	5.76	7.65	132.70	7.66	132.80
⋮						
5 / 28	20.80	2.38	7.82	205.52	8.51	353.65
5 / 46	18.36	0.00	1.44	55.90	1.44	55.90
⋮						
6 / 20	22.44	0.01	4.60	237.70	4.61	238.00
6 / 30	17.16	2.71	7.35	185.80	7.36	185.90
⋮						
7 / 29	19.03	8.01	17.79	681.80	19.67	754.00
7 / 30	24.47	1.86	8.00	544.40	10.74	730.90
⋮						
8 / 3	24.93	4.10	18.08	454.50	18.1	455.00
8 / 6	25.46	3.79	15.53	538.10	15.58	539.70
⋮						
<b>average</b>	<b>21.85</b>	<b>3.17</b>	<b>8.13</b>	<b>279.57</b>	<b>9.16</b>	<b>337.47</b>

Table 6-11: Simulation results fleet  
Source: Author

### 6.5.3 Impact analysis - fleet

The fleet based impact analysis results are displayed in Table 6-12. The S<sub>10</sub> based consideration shows that even under the implementation of 13 charging stations, very low recharge energy is realised, so that within some of the considered days no system adaptations are possible (see vehicle 5 day 46 and vehicle 6 day 20). In order to increase the downsizing potential for these vehicles, vehicle

specific charging stations would need to be implemented in reference to the case specific results.

Changing to the OCSLM approach of charging station allocation, each vehicle is enabled to recharge. For the vehicles 7 and 8 the maximal downsizing potential can be realised, whereas the maximum potential cannot be used for the remaining vehicles of this fleet as long as charging station allocation targets to increase the fleet’s overall recharge energy.

As Table 6-12 shows, the absolute difference in matters of battery capacity reduction from  $E_{ij10}$  to  $E_{ij}$  is comparably low, so that impact analysis results majorly correspond. The value of vehicle 4 day 7 decreases from  $E_{ij10}$  to  $E_{ij}$ , whereas the overall system energy balance increases. This shows that the relocation of idle time potentials can decrease individual recharge energy in order to increase the overall additional energy input in line with the OCSLM target definition.

Day	Battery capacity reduction	Required capacity	CO2 Reduction battery	Reduction process energy	CO2 reduction process	Additional energy efforts movement	Additional energy efforts movement	Transmission losses
$S_{10}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
3 / 4	9.79	9.89	734.17	2.92	0.174	x	x	0.21
3 / 5	7.07	12.61	530.32	1.46	0.110	x	x	0.27
⋮								
4 / 2	10.06	9.62	754.50	2.31	0.177	x	x	0.56
4 / 7	10.71	8.97	803.34	2.31	0.178	x	x	0.63
⋮								
5 / 28	7.18	12.5	538.83	0.00	0.000	x	x	0.26
5 / 46	0.00	19.68	0.00	0.00	0.000	x	x	0.00
⋮								
6 / 20	0.00	19.68	0.00	0.00	0.000	x	x	0.00
6 / 30	4.71	14.97	353.11	2.48	0.222	x	x	0.30
⋮								
7 / 29	13.06	6.62	979.68	2.36	0.186	x	x	0.89
7 / 30	10.89	8.79	816.83	2.36	0.127	x	x	0.2
⋮								
8 / 3	13.76	5.92	1,031.85	2.36	0.125	x	x	0.45
8 / 6	15.74	3.94	1,180.80	4.73	0.106	x	x	0.42
⋮								
average	8.58	11.10	643.62	1.94	0.117	0	0	0.35



$E_{ij10}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
3 / 4	12.64	7.04	947.70	2.92	0.174	1.51	0.16	0.47
3 / 5	4.78	14.9	358.26	1.46	0.110	0.14	0.02	0.06
⋮								
4 / 2	9.34	10.34	700.67	2.31	0.177	0.48	0.06	0.49
4 / 7	12.93	6.75	970.10	2.31	0.178	0.89	0.12	0.84
⋮								
5 / 28	13.99	5.69	1,049.58	2.68	0.197	1.25	0.16	0.86
5 / 46	4.26	15.42	319.21	0.00	0.000	0.3	0.04	0.16
⋮								
6 / 20	8.87	10.81	665.31	2.48	0.198	1.44	0.20	0.51
6 / 30	10.17	9.51	762.52	2.48	0.222	1.00	0.15	0.81
⋮								
7 / 29	15.74	3.94	1,180.80	4.73	0.372	7.39	0.98	1.96
7 / 30	15.74	3.94	1,180.80	4.73	0.255	5.11	0.47	0.88
⋮								
8 / 3	15.74	3.94	1,180.80	4.73	0.249	4.36	0.39	1.99
8 / 6	15.74	3.94	1,180.80	4.73	0.106	6.21	0.23	1.71
⋮								
average	11.66	8.02	874.71	2.96	0.187	2.51	0.25	0.90

$E_{ij}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
3 / 4	15.74	3.94	1,180.80	4.37	0.262	2.54	0.26	0.80
3 / 5	7.15	12.53	536.49	1.46	0.110	0.70	0.09	0.28
⋮								
4 / 2	11.73	7.95	879.79	2.31	0.177	0.70	0.09	0.71
4 / 7	11.73	7.95	879.79	2.31	0.177	0.70	0.09	0.71
⋮								
5 / 28	14.81	4.87	1,110.47	2.68	0.197	2.15	0.27	0.94
5 / 46	4.26	15.42	319.21	0.00	0.000	0.30	0.04	0.16
⋮								
6 / 20	8.87	10.81	665.31	2.48	0.198	1.44	0.20	0.51
6 / 30	10.18	9.50	763.41	2.48	0.222	1.00	0.15	0.81
⋮								
7 / 29	15.74	3.94	1,180.80	4.73	0.372	8.17	1.09	2.16
7 / 30	15.74	3.94	1,180.80	4.73	0.255	6.86	0.62	1.18
⋮								
8 / 3	15.74	3.94	1,180.80	4.73	0.249	4.36	0.39	1.99
8 / 6	15.74	3.94	1,180.80	4.73	0.106	6.21	0.23	1.71
⋮								
average	12.29	7.39	921.54	3.08	0.194	2.93	0.29	1.00

Table 6-12: Impact analysis results fleet

Source: Author

The average values of the fleet examination show that the combined optimisation lowers the results for specific vehicles and days while maximising the overall outcome. Within the fleet optimisation, the exhaustion of potentials in all categories

remains behind the maximum values (see Figure 6-12) as the target definition demands for overall system improvement.

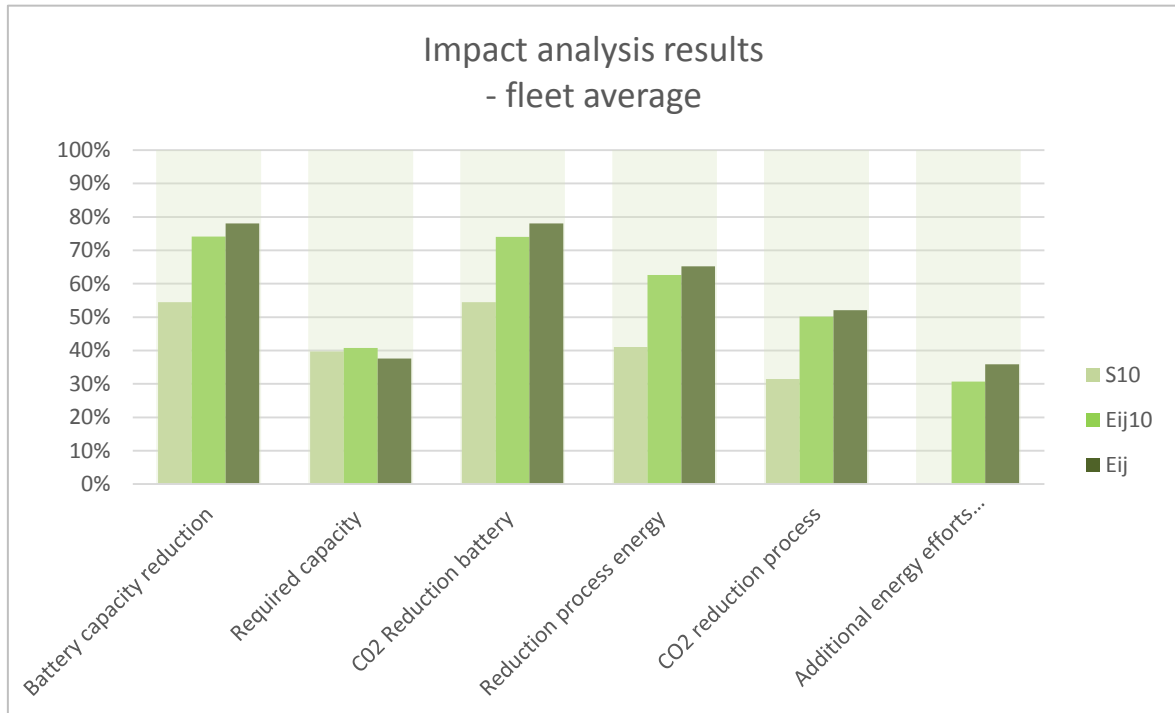


Figure 6-12: Impact analysis results fleet  
Source: Author

## 6.6 Chapter summary

The presented chapter demonstrated the general applicability of OCSLM to single and multiple case investigations. Its utilisation in different production facility locations and on vehicles with different production related transportation functions proved its broad applicability also for different production facilities.

The procedure of OCSLM execution for all vehicles is identical whereas the input data in reference to the explanations of chapter 5 [p.105] needed to be adjusted to the specific geographic environment. In doing so, OCSLM can be adapted and react to case specific requirements and conditions.

The results of the executed investigations showed corresponding values and system behaviour in order to demonstrate and confirm the taken approach. The analyses' outcomes present the answers to the research questions introduced in section 3.2 [p.57], whereas adequate reference is taken within the critical discussion of the following chapter.

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# CHAPTER 7

## CRITICAL DISCUSSION

### 7.1 Introduction

The presented chapter is dedicated to the review and interpretation of the research project results, its corresponding findings based on the performed location-allocation modelling and the executed case study. The subsequent considerations examine the benefits and advantages as well as the limitations and weaknesses of the performed research project including the developed research methodology, OCSLM, analysis outcomes and its specific interpretations. Related descriptions explain the handling of these weaknesses and can therefore be considered as recommendation for the execution of related or connected research. Furthermore, this chapter defines the research project and the generated results within the context of its specific research environment.

### 7.2 Research parameter analysis

In line with the explanations on related research work in the field of electric vehicle charging and charging station allocation it can be stated that the operated kind of research requires a profound basis of information and data, as well as a comprehensive, structured and target specific framework for its outcome evaluation. The comprehensive literature review exposed that existing research already identified most important performance indicators for material handling and also highlighted the developments in this field in order to constantly increase and improve operation efficiency. In contrast to this, the review on combined process and energy performance indicators as well as data showed a lack of scientific investigation and information. Literature and the executions of relevant data collection, processing, analysis and evaluation revealed the complexity of the subject and identified the shortcomings and the lack of scientific investigations being applicable as reference models. Even in times of increased attention to energy related topics, the literature review showed a superficial treatment and generation of energy numbers only in both industrial and road electric vehicle application. The review

of energy consumption figures in industrial application showed a similar treatment of these figures. While energy consumption data was available and partly stored, the data lacked usability due to the unspecified data structure and its missing granularity. The need for more specific investigations and the development of a structured framework for energy consumption data generation induced the development of a dedicated and standardised framework for energy and process data generation and collection. Energy consumption values according to the presented approach SECA were generated based on a standardised procedure, so that individual values are generally valid and applicable for other purposes. Process data collection was executed on specific data loggers in order to generate a high resolution of material handling inherent process steps of two records per second. In a post research review, the high resolution of data is seen as a beneficial aspect in order to achieve detailed insights into individual process steps and to increase the knowledge on the nature of break spots (see Table 7-1). For the simulation of charging station infrastructure allocation a lower resolution can be applied in order to lower the volume of data to be stored. Within the analysis and evaluation of break times low duration spots of few seconds only can contribute to increased recharge energy but showed lower impact to the general placement of charging stations, so that a lower resolution might lead to the exclusion of these spots. The impact from lower data resolution and by this the exclusion of low duration break spots to charging station allocation have to be investigated in a separate examination.

Typical duration	Process specific	Occurrence	Other specifications	Fraction
1 - 10 sec	No	Frequent	In front of crossings, intersections, gateways	20.6%
1 - 25 sec	No	Non-frequent	Random distribution within facility	
10 – 180 sec	Yes	Frequent	In front of pick-up and delivery zones Include process preparation/execution	49.6%
10 – 60 min	No	Frequent	Break time	29.8%

Table 7-1: Charging potential identification

Source: Author

The major fraction of usable charging times showed a frequent geographic occurrence and was identified to range from ten to 180 seconds. Shorter, process

related break times showed a lower occurrence of 20.6%. The integration of short break times and accumulated break times showed a positive contribution to additional UBE, but did not notably change charging station allocation.

Referring to contact based charging with its current technical restriction of average connection times of approximately 45 seconds (see subsection 2.3.3.3 [p.24]) results in the exclusion of about 37% of the possible, process specific charging times. In respect to the fraction of short period charging times of 20,6% (see Table 7-1), only 61,1% of the total possible charging times are available for occasional charging.

While charging station allocation for road electric vehicles is subject of intensified attention, similar or connected investigations for industrial application have been neglected so far. As the review of existing models of section 2.6 [p.33] revealed, none of these was applicable to the research execution due to the defined target of research, whereas individual findings of these models contributed important details and aspects to the development of a subject specific framework and model. The lack of investigations in industrial application constituted a surprising result of the literature review as most experience in reference to the implementation of electric vehicles was assumed to be available in this field.

The design of a dedicated location-allocation model served as basic tool in order to generate information on the charging potential, whereas this research project highlighted the importance of a subject specific calculation algorithm. The generated simulation results as intermediate outcome showed differences in recharge energy based on the definition of the applied covering distance. The reference to an endogenous covering distance resulted in increased energy values of +40% to +60% (see Figure 7-1) in reference to existing approaches based on exogenous covering distance definitions as represented by  $S_{10}$ . The case study executions showed alternating impact from break time occurrence and duration as well as the choice of an appropriate covering distance. In general, long break times have high impact to charging station allocation, so that the optimised charging stations are allocated close to maximal charging spots. The use of an endogenous covering distance relocates charging station allocation from the maximal charging spots in order to integrate as much additional volume as possible based

on the maximal gradual covering approach. The impact from the choice of a covering distance definition increases with lower recharge energy to be available and break times to be more equal in reference to their location and duration.

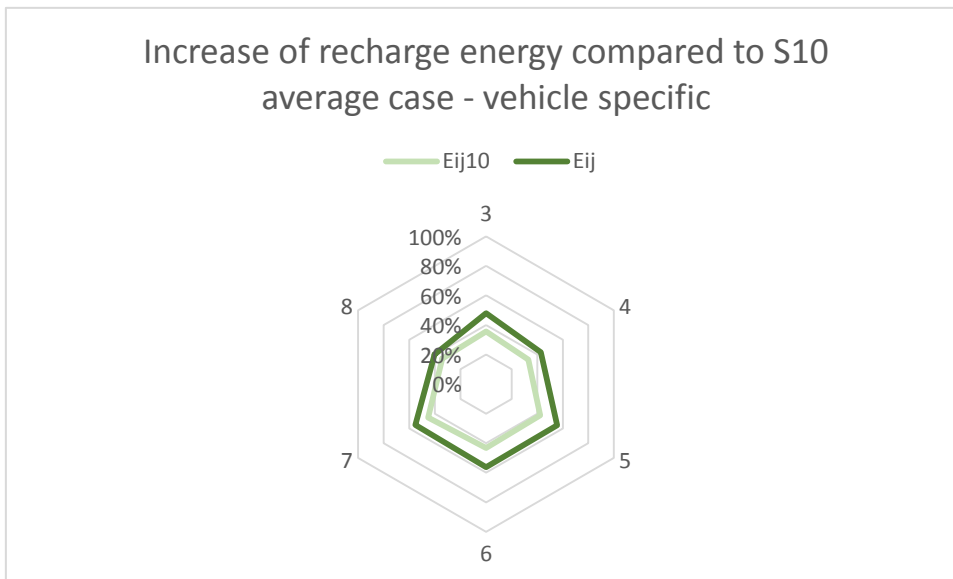


Figure 7-1: Covering distance related growth of recharge energy

Source: Author

In addition to the results provided on theoretical and practical charging potentials and the fraction of its usage, information on additional drive distances was generated. The simulation results showed alternating values on drive distances, energy consumption, recharge energy etc. on vehicle and day basis. This highlights the importance of specific investigations for different applications as differences in process and use patterns influence the results on occasional recharging. The comparison of the simulation results on recharge energy and additional drive distance showed an increase of these values from  $S_{10}$  over  $E_{ij10}$  to  $E_{ij}$ , whereas these numbers in reference to the defined process parameters (see section 2.4 [p.26]) counteract each other, so that a subsequent analysis reviewed the impact to system efficiency and sustainability.

This impact analysis showed the influence from process sequences, structures and characteristics to the vehicle battery downsizing potential. An increased value of recharge energy is not necessarily synonymous to an increased downsizing potential as other factors such as process energy consumption, additional drive distance, transmission efficiency and minimal required battery capacity influence the vehicle (component) design. In addition to this, the analysis on the input and output parameters illustrated that in order to achieve the maximum battery capacity reduction as a measure of increased resource efficiency it is not

generally necessary to maximise and use the maximum of recharge energy. As the analysis indicated, the level of recharge energy being necessary for maximum battery downsizing ranged from 6kWh to 12kWh, so that within some of the cases the achieved recharge energy of  $S_{10}$  and  $E_{ij10}$  were sufficient at lower additional energy efforts. Under the consideration of additional energy efforts and losses, the requirement for case specific investigations becomes apparent in order determine the preferable alternative among the different covering distance definitions.

Decreasing the battery capacity and by this battery mass enables additional energy savings in the range from 2% to 5%, which need to be evaluated in reference to the additional energy efforts for additional driving due to charging station approaching and additional transmission losses of contactless over conductive charging.

In addition to the displayed results of chapter 6, i.e. the generated output parameters, subsection 7.4.3.1 and subsection 7.4.3.2 compare the case study results towards system efficiency and sustainability in a cost based respectively CO<sub>2</sub> emission based, final consideration.

In general it can be said that the reference to the endogenous covering distance and the developed framework of OCSLM increases the amount of recharge energy and enables improved battery sizing, whereas the results can only partially be generalised, so that for the integration of a charging infrastructure for occasional recharging, individual case adapted investigations are necessary. Furthermore, investigated cases need to be reviewed towards their consistency respectively changes of the material handling processes and structures in order to maintain the achieved level of efficiency and system availability.

### **7.3 OCSLM application**

The following executions examine the application of OCSLM and its integration into industrial material handling processes and highlight important aspects learned from tool application. The section first explains the benefits of operating OCSLM on company and scientific level and then refers these to the general conditions and requirements for the application of OCSLM.

### 7.3.1 Benefits

In line with the executions on OCSLM output, i.e. the results generated by its operation, the tool provides several types of information being of interest to both commercial enterprises and science. By this, OCSLM is designed in order to provide (see also Figure 7-2):

- (1) a practice-oriented source of information and decision support to economic entities
- (2) new research findings

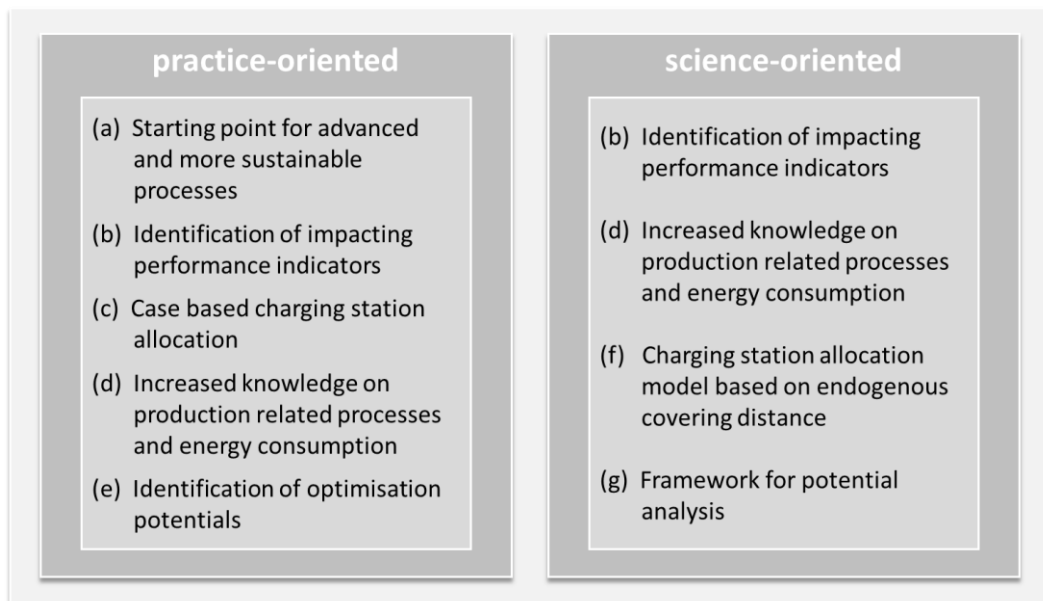


Figure 7-2: Benefits of OCSLM

Source: Author

In a practice-oriented consideration, OCSLM serves as a starting point for producing business entities in order to achieve more advanced sustainable production processes. The OCSLM approach fosters increased system efficiency and availability of production resources in line with the explanations of Chow (1990 – see section 2.3 [p.15]). Companies are given additional information and guidance by the identification and analysis of critical performance indicators being based on existing scientific investigations. These indicators are the basis for the determination of optimised charging stations allocations for occasional recharging in reference to the prevailing research environment infrastructure and processes, so that decision makers are served with a tool to facilitate the implementation practice. The basis of this location decision simulation is the integration of case



specific process characteristics, in order to integrate process immanent specifications and to identify system optimisation potentials in reference to energy supply, storage and consumption. This information increases the knowledge on production related processes and referred energy consumption representing different functions of cost. In its final consideration, OCSLM execution highlights the potential of occasional power supply to realise resource savings and to increase sustainability within system design of material handling equipment being subject to system component downsizing and optimisation. By this, OCSLM depends on the quality and granularity of input data and information. The more detailed and realistic the input, the more realistic and informative the output, so that the informative character of the generated results depends on the willingness and efforts of industrial business entities to be taken. In industrial environments with low equipment use rates, low data quality can be inserted as usable break times are assumed to be sufficiently available. In contrast to this, high use rate environments with high sensitivity to process interruptions and high demand for equipment availability require a higher resolution of process data and a profound knowledge on energy consumption. In this application, occasional recharging is limited to shorter interim charging times under the premise to not disturb manufacturing processes, so that the allocation of break times and the duration to be integrated require high precision.

From a scientific perspective, OCSLM programming is based on the investigation, analysis and integration of relevant performance indicators in order to integrate subject specific values and to increase knowledge about its consistence. The processing of basic data on energy consumption in combination with more detailed process information fosters knowledge on the characteristics and the interaction of these elements, whereas further investigations in alternative research environments will have to prove or disprove the validity of these results in other applications.

The development of the charging station location model for occasional recharging formed a key element of the pursued research project by highlighting a previously unattended specification of charging station allocation which integrates a function based covering distance model and re-evaluates process components as poten-

tials for increased systems efficiency. This model constitutes a further specification of existing location-allocation approaches by integrating a more detailed and realistic perspective on processes, energy consumption and the definition of demand and covering distance to existing scientific work. The combination with a subsequent impact analysis completes the development of the framework for a comprehensive potential analysis that adds an economic and ecologic perspective to the existing focus on demand coverage. Its execution and results provide evidence regarding the significance of increased knowledge and work in this field of research. The development of the subject specific location framework contributes to new knowledge in the field of charging station allocation and provides a first step into investigations in this field.

In reference to the findings addressing practice- and science-oriented components, benefit (a) of Figure 7-2 refers to its practical application, whereas (g) addresses scientific considerations and requirements. (b) and (d) simultaneously constitute benefits for both purpose groups and cause no additional efforts for its generation. The relation of (f) to (c) and (g) to (e) emerges from the necessity for initial scientific investigations and the development of a verified and valid research framework which subsequently is practically applicable. The initial phase of the research project expected more reference models and approaches to be available in order to serve as fundamental basis for the project execution. Due to low availability respectively the lack of adequate reference models the research project and framework presents a first approach to the optimisation of charging station allocation for occasional recharging and therefore addresses further improvements to be done in order to cover with further technological developments and changed research target definitions. The operation of OCSLM in case specific investigations showed the impact from research to practical application and backs up the pursued research project approach which leads from the scientific development and design (chapter 3 to 5) to its practical case application (chapter 6). The design of OCSLM allows its general application to alternative research environments, so that periodic reviews and adaptations of the model, the research object and the input data will have to keep up and maintain the quality level of research.

### 7.3.2 General conditions and requirements

OCSLM is based on the defined performance indicators and parameters as per previous explanations. In line with the explanations of chapter 4 [p.89], energy consumption data in reference to SECA can be applied to similar handling equipment, so that additional data collection is no obligation. For alternating equipment, quantitative data collection in line with the explanations on the generation of SECA is inevitable in order to maintain the appropriate quality of results. The reference to calculated numbers is possible, whereas the analyses of section 4.2 [p.89] showed the deviation in values. This demand for specific energy consumption values presents additional efforts to be taken for investigations in alternative environments, so that the continuing low availability of appropriate energy consumption values may prevent OCSLM from its widespread application in an initial phase, respectively fosters its use under the shortcoming of imprecise results.

Process data, including operation and idle times, can be retrieved and recorded based on alternative data collection equipment or procedures, whereas the quality of data directly impacts the validity of the investigation outcome. Meanwhile, process recording equipment is commercially available and easy to install, so that the integration of low quality data due to the efforts of process data collection should be avoided. As process data collection on man-guided vehicles includes information on driving behaviour and patterns of the operators, these need to be informed about the data collection process. Operators have to be informed about the possibility to not participate in the data collection and/or to have the right to resign from the process data collection at any time (see Appendix E). Furthermore, collected data should be representative in its processes and the size of samples. Throughout the executed data collection approaches, process data was anonymised in reference to vehicle and operator numbers, shift and day of recording in order to decrease resistance, upkeep ethical principles within the investigations and to assure recording of standard operation processes. This procedure decreases the quality of results as the analyses and simulations can not be set in a timely relation and by this prevent the realisation of a capacitated simulation approach.

The processing of data, operation of simulations and the evaluation of results should be executed by competent staff in order to ensure the correct execution

and deduction of results. The framework design requires no personal engagement or expertise, so that results are free from subjective operator influence.

Simulation and analysis results are based on the generation of optimised charging station allocation(s) in reference to maximal energy input, i.e. maximal gradual coverage of demand, under the consideration of production facility obstacles such as walls or other fixed elements (see subsection 5.3.1.2 [p.128]). Due to the continuous modelling approach, final charging station allocations need be reviewed for the field implementation based on process routing and spatial considerations in order to prevent process and operations impairment. This additional step can only be operated in reference to indeed knowledge on case specific production and supply processes as well as routing in order to prevent impractical implementation and the disturbance of other processes.

## **7.4 Case study results**

As previously mentioned, the investigated case study and its results illustrate the potential of integrating a system for occasional recharging for electric vehicles in a line assembly manufacturing environment. Due to the individuality of processes, process structures and characteristics, the generated results lack usability as a general benchmark, whereas the OCSLM framework and defined procedures are valid and applicable to any process on electric engine driven vehicles being subject to the provision of adequate data. At this point it needs to be highlighted that OCSLM output is based on the process and energy based input, so that changing the input data is of direct influence to the results. Consequently, process choice, data collection and data quality as well as the determination of case related assumptions are important factors for the derivation of conclusions. Changes in one of these dimensions will impact the results, so that a balanced and equal quality of all data and information input is required. The framework design and execution provide the required level of flexibility and adaptability in order to address the complexity of the research subject.

### **7.4.1 Short term vs. long term investigation**

The course of OCSLM case study execution showed differences from case to case but also highlighted differences in reference to individual days within individual vehicle investigations. Recording of several days, i.e. shifts, of one vehicle

illustrated differences in reference to process sequences, drive routes and distances as well as recharge energy potentials. As the integration of an electric vehicle charging infrastructure has the target to increase or at least to assure constant system availability, the data basis, i.e. the processes, are of crucial role to the evaluation of system dimensioning. The analyses highlighted the impact from minimal recharge energy as bottle neck to the realisation and use of process immanent potentials. Single day investigations in reference to process and energy monitoring represent a snapshot in time, so that single day investigations may lead to insufficient system design and system energy shortage.

Figure 7-3 shows the difference from the reference to the day of minimal to the average recharging potential of the considered vehicles over all monitored days. The weakness of determining the battery capacity based on the recharge energy being available in average, as representative of a single or short term process monitoring approach, is illustrated by the difference in values from the minimum to the average cases.

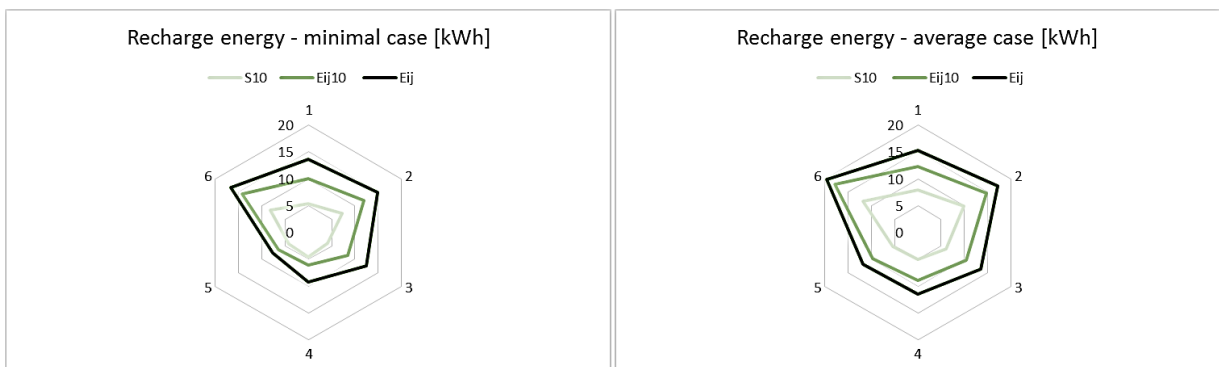


Figure 7-3: Minimum vs. average recharge energy  
Source: Author

The advantage of long term investigations over single shift examinations is based on the more comprehensive data structure that allows the determination of low recharge energy potentials. This minimum potential needs to be balanced by system design in order to avoid system downtimes due to energy shortcomings. The realisation of long term investigations does not prevent systems from energy shortage as extreme cases rarely occur and their integration would counteract the pursued optimisation approach. System design should be oriented on average case results in order to approximate to the optimum case. Data reviews need to analyse the standard deviation and the appearance of minimum cases in order to predict system outages and to provide an additional decision variable for system design. Therefore, long term investigations are a time intense alternative to

improve predictability of system outages, but increase the long term efficiency of system design. Furthermore, in environments with high deviations, low standardisation and stability of processes, OCSLM lacks applicability as the charging station allocation model is based on the inserted choice of process sequences and by this only represents an optimised solution for the inserted cases.

#### **7.4.2 Single vs. fleet investigation**

In line with the explanations on process data collection in reference to short vs. long term investigations, further influence on the analysis results emerges from the investigation pre-setting. The basic assumption of three charging stations to be approachable by each considered vehicle results in different values for individual and fleet investigations (see Figure 7-4). Within the individual vehicle investigation, charging stations are adapted to the vehicle specific process sequences and routing, meaning that the degree of battery downsizing reaches higher values than within the fleet investigation. In the individual vehicle investigation and the  $S_{10}$  covering distance definition, battery capacity can only be downsized to the maximum value for vehicle 8, whereas the fraction of full downsizing achievement is higher in reference to the function-based covering distance approach. Due to the battery capacity limitation the used potentials of  $E_{ij10}$  and  $E_{ij}$  show the same results within the individual examination (see top of Figure 7-4), whereas the fleet investigation with lower individual recharge energy highlights the additional benefit from increased recharge energy by the  $E_{ij}$  definition. The illustration of required battery capacity shows the impact from the covering distance and the analysis target definition to the overall results. Within the illustrated investigation, all vehicles were able to approach a minimum of three charging stations. In order to increase the individual recharge energy and to decrease the level of required battery capacity, additional charging spots can be added to the fleet investigation. The integration of these additional charging stations need to be adapted to the case specific requirements, for instance to decrease the battery capacity of specific vehicles or to ensure the maximal battery downsizing of all trucks investigated. The approach to stepwise increase the number of charging stations requires additional simulation execution in order to calculate the impact to individual vehicles and constitutes a mixed form of Maximal Covering Location and Location Set Covering Modelling. From the individual vehicle examinations it

can be derived that the integration of 18 charging stations would result in minimal required battery capacity as displayed in the top of Figure 7-4.

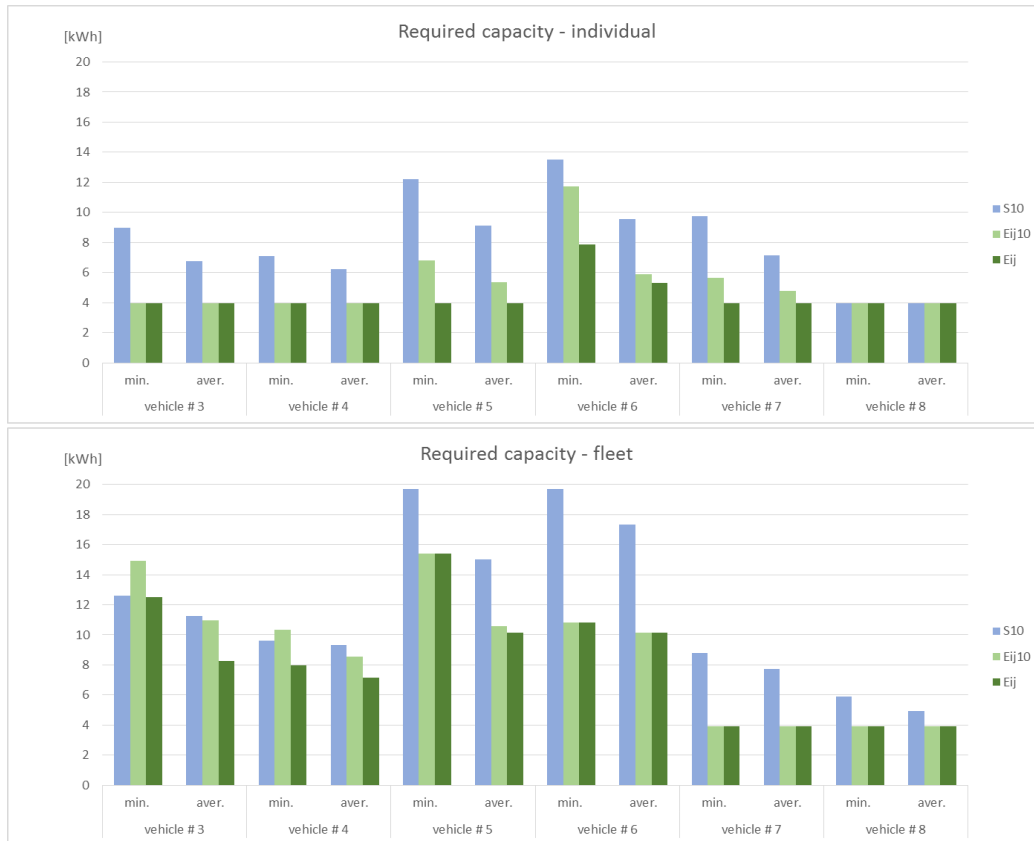


Figure 7-4: Results individual (top) vs. fleet (bottom) investigation

Source: Author

The execution of individual vehicle analyses generated interesting and important information on the impact of occasional, contactless charging to the individual energy balance including information on drive, routing and energy consumption patterns with relevance to production planning and design being of interest to science and practice. The results give information on how and where energy is consumed as well as the individual load profiles, so that production planning can integrate these values into their material and equipment planning. The same results are of interest to science, as these present a valid basis of information and benchmark on energy consumption values and behaviours. The individual results on battery downsizing give information on its maximal potential being achievable as a first evaluation step.

The arrangement and planning of an electric vehicle energy supply infrastructure should be based on fleet investigations in order to address budget requirements, i.e. the maximum number of charging stations. From fleet simulation executions,

the impact from charging station implementation to individual vehicles can be deduced which represents a more realistic and practicable output.

### 7.4.3 Analysis outcomes

The previously displayed and explained research output, i.e. the results of system adaptations based on occasional recharging, are reviewed towards its impact to increased system efficiency and sustainability.

As defined by Chow (1990) equipment availability is an important factor to material handling system's efficiency (see subsection 2.3.1 [p.16]), so that the target of the research investigation was defined to evaluate the potential of occasional recharging in material handling to further increase system efficiency at constant equipment availability.

In line with the description by Naef (1998:51), efficiency can be defined as the relation of revenue to effort, meaning that in addition to the reduced battery mass as a measure of decreased resource usage, the ratio of energy saving to additional energy effort serves as an efficiency assessment standard. Figure 7-5 shows the process efficiency parameters for the investigated vehicles based on minimal recharge energy examinations, which in this consideration also represent the parameters for sustainability. The reduction of process energy results from decreased vehicle mass due to battery downsizing and includes the values of the self-reinforcing effect from battery mass downsizing to reduced energy consumption to further battery mass reduction. The analyses showed a low impact to decreased energy consumption from this effect of 0.1% to 0.3%, due to the high energy density of the lithium batteries which results in low weight batteries, meaning that additional battery mass reductions are of minor importance.

According to Figure 7-5, for five of six of the data sets (except of vehicle 7) additional energy efforts for charging station approaching are lower compared to the process energy savings due to the decreased vehicle mass, so that in reference to process investigations a positive energy balance results. In reference to the explanations on charging equipment for occasional recharging based on contactless power transmission (see subsection 2.3.3.3 [p.24]), additional losses need to be considered due to lower power transmission efficiency. Figure 7-5 shows the amount of transmission efficiency losses that have to be considered, so that



due to these additional losses in comparison to conductive recharging the overall energy balance turns negative in the process-based consideration. At this juncture it can be identified that due to the additional energy losses at an efficiency of 89% for occasional recharging based on contactless power transfer, occasional recharging has no additional positive impact on the process energy consumption. This highlights the importance of technical transmission efficiency improvements in this field in order to adapt transmission losses to the conductive efficiency standard.

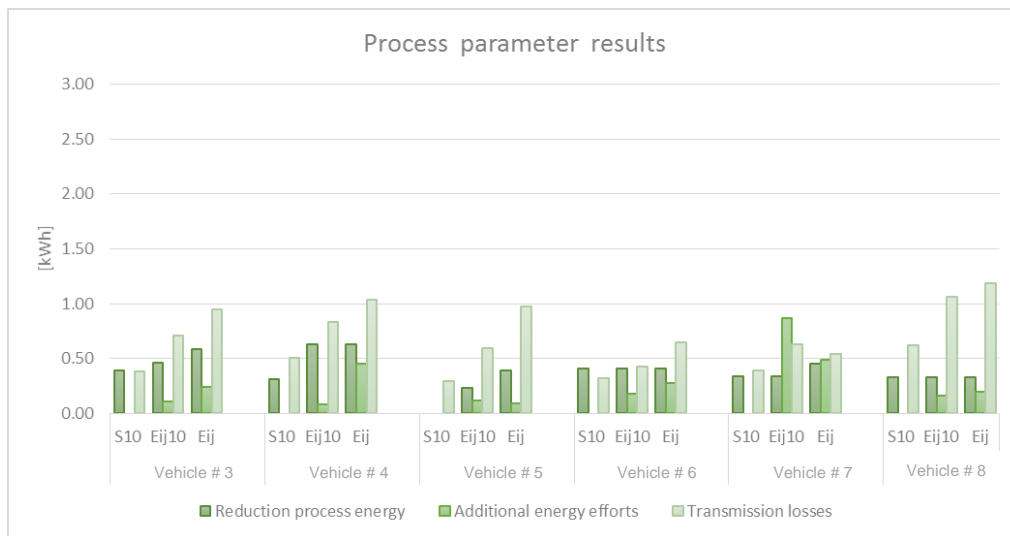


Figure 7-5: Process efficiency parameters

Source: Author

#### 7.4.3.1 Efficiency based outcome

In addition to the above process related potential evaluation, an overall efficiency consideration integrates all parts, such as battery and energy cost into a system life cycle evaluation, whereas the disposal of batteries before the calculated, nominal battery was not explicitly investigated within a separate sensitivity of the executed analyses. This comprehensive investigation highlights the meaning of contactless occasional charging to the system efficiency and sustainability balance.

The cost based efficiency evaluation compares the fixed and variable cost of conventional operations with the integration of a contactless charging infrastructure

for occasional recharging. General components of the efficiency evaluation consist of the fixed battery cost<sup>3</sup> in reference to the respective process energy demand<sup>4</sup>, whereas further cost for the charging stations were not included. This is based on the fact that contactless charging systems are still within the design phase for industrial truck recharging without a reliable cost structure and that charging station cost are expected to correspond to the cost of conventional plug-in charging solutions. Variable process cost as per Figure 7-5, such as the energy savings by reduced battery mass as well as the additional efforts based on the additional drive distance and transmission losses are part of this examination. The variable cost are calculated in reference to the battery life cycle based on 220 work days per year, each representing one full cycle equivalent. By the reference to a total of 2,500 full cycles, the battery life cycle was determined to be 11.4 years as scale for the variable cost integration.

Figure 7-6 shows the efficiency evaluation based on the battery life-cycle for the individual vehicle investigations. In reference to the process energy demand, the required battery capacity without a recharging system for occasional recharging was determined as the standard of comparison. The values for  $S_{10}$  include occasional recharging being based on the corresponding covering distance approach. The values of  $E_{ij10}$  and  $E_{ij}$  are based on the previously described improvements on charging station allocation that allow further battery size adaptations. The displayed values within Figure 7-6 include the additional energy savings and efforts based on the calculated battery life-time of 11.4 years.

In contrast to the results on process energy that highlighted increased energy efforts for contactless recharging, the comprehensive efficiency evaluation shows the compensation of these additional variable process cost by the savings on the fixed battery cost.

The results on vehicle 8 show that the  $S_{10}$  location-allocation modelling is more beneficial for that case. This is based on the fact that full battery downsizing is achieved by the  $S_{10}$  covering distance for vehicle 8 as well, so that the additional energy efforts for charging station approaching lower the result of  $E_{ij10}$  and  $E_{ij}$ ,

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<sup>3</sup> € 360,- per kWh of lithium battery (see Giménez- Gaydou et al. 2016)

<sup>4</sup> Cost of electricity was assumed to be € 0.08 / kWh

while no more system adaption can be achieved due to the defined system limitations.

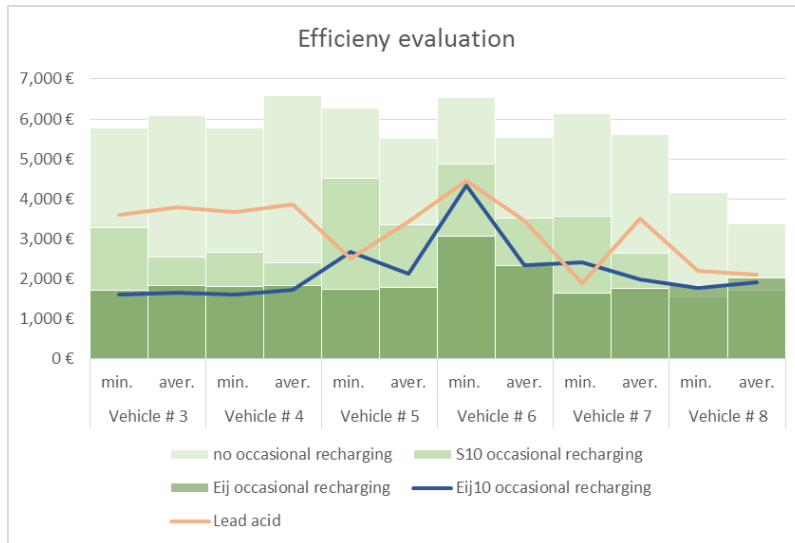


Figure 7-6: Cost based efficiency evaluation

Source: Author

For increased comparability to the existing practice with the majority of vehicles being equipped with lead acid batteries, Figure 7-6 displays the calculated battery cost in reference to the simulated process energy demand being required for constant system availability. As illustrated, the cost of lead acid batteries, which cannot reasonably be used for occasional recharging, exceed the cost of lithium ion batteries in reference to the described battery capacity optimisations, enabled by occasional recharging and based on optimised charging station allocation. This highlights the technical potential of lithium ion batteries in combination with occasional recharging to contribute to increased system efficiency and by this can offer an essential step in changing man-guided material handling system design from the mature lead acid technology towards increased usage of state of the art lithium ion technologies. Furthermore, the results elucidate the importance of a dedicated framework for charging station allocation and, by this, endorse the significance and contribution to new knowledge of the executed research project.

#### 7.4.3.2 Sustainability based outcome

In line with the previous outcomes on system efficiency, the following examinations focus on the sustainability factor of occasional recharging by referring to the volume of CO<sub>2</sub> emissions as a corresponding standard for system ecology.

The determination of the volume of CO<sub>2</sub> emissions is based on the approach of battery life cycle which includes the fixed CO<sub>2</sub> emissions for battery production, i.e. the savings on CO<sub>2</sub> emissions by battery downsizing<sup>5</sup>, as well as variable CO<sub>2</sub> emission components. Emission savings arise from energy consumption savings that are set in contrast to the additional emissions caused by additional drive distances as well as additional transmission losses of contactless to conductive power transmission. The consumption of one kWh of electricity was therefore assumed to emit 564g of CO<sub>2</sub> in reference to an energy mix of renewable and fossil fuels (Kranke, Schmied and Schoen 2011).

Figure 7-7 shows the overall material handling process CO<sub>2</sub> emissions as reference line for the additional emissions being generated for battery production and the integration of an occasional recharging infrastructure over the calculated battery life time. The results on 'no occasional recharging' are based on the battery capacity dimensioning of a lithium ion battery in respect to the investigated process energy consumption combined with conductive power transfer. Based on the approach of SECA (see subsection 4.2.1 [p.90]), process energy demand was determined and the battery capacity adapted to it in order to assure a constant system availability. The CO<sub>2</sub> emissions of this investigation category refer to the fixed battery production including losses of conductive charging and account for an average of 6.38% of the total investigation CO<sub>2</sub> emissions. Referring this value to the battery technology that is more often installed in real world application at the time of research execution, shows that the generated CO<sub>2</sub> emissions for a comparable lead acid battery would result in increased emissions of +36% within all investigated data sets.

Compared to the base case on conductive charging and lithium ion battery, the S<sub>10</sub> investigations display a higher energy consumption attributable to additional losses caused by the lower transmission efficiency of contactless power transfer which results in higher CO<sub>2</sub> emissions of +0.8% (7.18% of total emissions). The reference to E<sub>ij10</sub> shows a further average increase of emission of +3.92% (11.10% of total emissions); for E<sub>ij</sub> for +6.89% to a fraction of the total emissions

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<sup>5</sup> The production of one kWh of battery capacity of lithium ion battery results in the emission of around 75kg of CO<sub>2</sub> (Dell'era et al. 2015)

of 14.07%. These investigations show the impact from the integration of occasional recharging to increased CO<sub>2</sub> emissions, i.e. decreased ecology. In reference to the existing approaches of electric vehicle operations and recharging, the implementation of a charging infrastructure for occasional recharging increases the pollutant emissions caused by electrical charging, whereas the total impact in comparison to process related CO<sub>2</sub> emissions is comparably low. In order to address the demand for increased overall sustainability, especially contactless transmission efficiency as main contributor to increased emission of CO<sub>2</sub> was identified for further improvements in corresponding extent of approximately 5,49%.

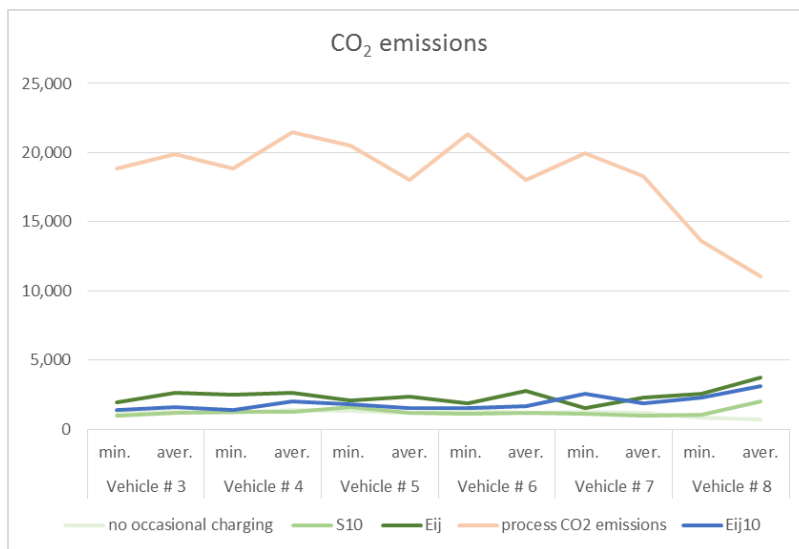


Figure 7-7: Case study CO<sub>2</sub> emissions [kg]

Source: Author

## 7.5 Research limitations and weaknesses

The developed methodology, as well as its uniqueness in the defined research environments have been described within the previous sections. Compared to existing models for electric charging station allocation on regular battery recharging, the allocation methodology for occasional charging is the only one to combine investigations on energy consumption and supply with the characteristics of process sequencing and routing in reference to process immanent potentials of man-guided material supply. Furthermore, the developed framework enables the result and solution evaluation in reference to efficiency and sustainability and thus supports improved decision making. However, based on the assumptions and the

structure of the research execution, the research framework contains certain limitations that impact the analysis outcomes, so that these shall be explained, discussed and justified at this point. Furthermore, the research project execution revealed certain obstacles and weaknesses that can be avoided within the replication of the framework execution within future investigations. The function of this section is to critically list and explain the nature of these limitations and weaknesses in order to describe their consequences on the generated results. For increased clarity, the limitations and weaknesses are categorised according to their occurrence within the research model design, the data collection or analysis phase.

### **7.5.1 Model limitations**

Under the review and consideration of alternative allocation models as per Appendix A, the development of the research and simulation model is based on a Maximal Covering Location definition. This model definition limits the optimisation execution to a given number of charging stations, so that the identification of the economically or ecologically most beneficial number of charging stations asks for an extra, stepwise sensitivity analysis. Therefore, the model design limits the general optimisation approach that determines the optimal number of charging stations being based on an efficiency or sustainability investigation to a stepwise and more time consuming approach.

A further limitation of the model is based on the design of OCSLM as an incapacitated approach that does not consider blockage of charging stations due to other vehicles or any other reason for inaccessibility. In respect to investigations on an increased number of vehicles within a fleet, the impact of this factor is not considered within OCSLM and has to be reviewed, i.e. needs to be integrated for larger vehicle fleets in order to ensure the achievability of simulation results within system application. The achievable charging potential is assumed to be of lower volume in its application than turned out within the incapacitated simulations. For the execution of the research project, this fact could not be avoided due to data collection standards and principles of ethics as explained in section 7.3.2 [p.178]. Furthermore, this influence can be evaluated to be comparably low within the executed case study as the fleet of considered vehicles consisted of six vehicles

only and the charging station allocation showed a dense network of charging stations, meaning that backup capacities existed.

In model design, the reference to energy consumption values according to the SECA approach can be seen as a system weakness. Due to the early stage phase of SECA based energy consumption values, a low range of energy consumption figures is available so far. Therefore, the execution on alternative material handling equipment, i.e. vehicles with higher or lower vehicle mass, differences in vehicle motorisation or the handling of higher payload classes require the identification of additional, specific values. Nevertheless, the reference to a standardised and comparable scale of energy consumption can be seen as a milestone for the further developments in this field of research. Ongoing trends in energy monitoring foster the generation of further SECA values in different applications and, by this, will increase and facilitate the usage of the developed framework.

### **7.5.2 Limitations of Data Collection**

Within the executed research project being based on a single, complex case study, data collection is an important aspect by constituting the fundamental input of information to the analysis. In line with the previous differentiation, the limitations within data collection are subdivided into its affiliation to energy and process data.

On the whole, the reference to Standardised Energy Consuming Activities constitutes a dedicated design approach being inspired by consumption figures of combustion engine automobiles. Owing to its novel character for electric vehicles, respectively for industrial trucks, and manufacturing functions as well as the lack of similar information in this field, the generated values lack comparability, but therefore constitute a first, validated and reliable reference model as per chapter 5.4 [p.140]. The lack of comparative values highlights the necessity for further SECA generation in order to increase the data base on comparable and combinable energy consumption values.

SECA process energy consumption values in the described application are based on operator guided material handling equipment, so that energy consumption values can alternate in reference to operator specific drive patterns. Within the

SECA generation of this research project, operations were executed under maximal vehicle performance in matters of acceleration. Therefore, the monitored energy consumption figures are assumed to be of high level of energy consumption, i.e. above average. Data verification and validation showed the reliability of the results, whereas SECA figures still present average and approximated values. As the investigations in this field refer to a human activity system, data is subject to operator specific behaviour and therefore needs special attention. Within OCSLM based simulation design and operations, average vehicle velocity constitutes one of the vehicle specific input parameters (see worksheet 'info' in Figure 5-11 [p.134]), so that SECA values are adapted to individual vehicle drive patterns within simulation execution (see also subsection 5.2.3.4 [p.121]). The research project case study investigations for example showed slower handling and process related acceleration and processing with an average velocity at approximately 80% of the SECA generation as per section 4.2 [p.89]. Adapting the acceleration values within SECA calculation for this -20% results in decreased energy consumption of 13.82%. This example shows that the adaption and calculation of SECA in reference to its key performance indicators presents a key component for the provision of reliable and accurate simulations.

SECA generation within the research project was executed on four different sample trucks of the same model type in order to prove comparability and accordance of results. This procedure required the availability of structurally identical industrial trucks, the multiple installation and de-installation of measuring equipment as well as the repeated execution of similar process operations, meaning that a total of five days were spent for measuring execution and analysis. The measuring results showed energy data collection on one sample truck being sufficient as values corresponded and the increased number of tracked data did not contribute to increased or altered information. As the executed energy data collection presented the first of its kind, repeated and multiple investigations were operated to ensure data reliability.

Tracked process data in reference to process sequencing and routing is based on daily movement profiles within the described case study. Due to non-standardised and non-automated process routing, these investigated values differ from



day to day in respect to routing and operations, so that the station allocation results depend on the considered investigation samples. Applied process investigations showed process deviations from median values in respect to drive distance, i.e. overall energy consumption, operating hours, idle times and recharge energy of individual vehicles ranging from 8.8% in average up to 28.5% for the extreme cases. These values highlight the importance of the process data being a representative sample of the standard operations. Therefore, the executed analyses were based on a minimum and an overall average sample in order to investigate the analysis inherent deviations. This, as a general shortcoming of case study operations, highlights the deficient suitability of the investigation and case study results for generalisations. In contrast to this, the framework and simulation model can generally be applied in order to generate individual and replicable results being comparable in matters of their outcome.

The case study process monitoring resulted in a comprehensive data set of more than 1,250hours of process data, while process tracking was executed on six different vehicles. The data, being transferred to Excel, accounts for a total of 9,014,400 lines, i.e. an average of 57,600 lines per one shift, so that the tool and hardware for data analysis needed to be adapted in order to be able to process big data sets. Simulation execution therefore requires the 64-bit version of Microsoft Excel VBA as well as a high-performance processor.

Throughout the long term data analysis and the comparison of monitored days and weeks, the results showed similar process sequences and characteristics in reference to the sequence of working days. For further investigations in alternative environments data with high process standardisation sets of two weeks are therefore assumed to be sufficient to capture bottle neck days and the average case, meaning that the number of data can be lowered in order to reduce the data volume being required for the generation of reliable results as well as the total processing, simulation and analysis time. The granularity of process data within the executed research project with two tracks per second can be lowered to one or 1.5 tracks per second for pure charging station allocation and implementation. The precision of vehicle allocation is evaluated to be of lower importance, so that simulation operations can be shortened.

As process data collection on human steered material handling equipment records equipment movement profiles, at the same time it also records personal data on the system operators. Therefore data collection requires the approval of the works council which within the executed research approach turned out to be a time consuming process lasting about four months. This subsequently needs to be taken into consideration while organising and planning research executions.

In reference to the high dependency of the case study and analysis results to the process data and therefore process characteristics, a changing arrangement and operation of the manufacturing processes have a high impact to charging station allocation. The rearrangement of main processes of manufacturing impacts the organisation of auxiliary functions such as material provision and sequencing, so that in case of a changing production organisation, charging station allocation and all subsequent analysis steps are subject to revision. This requires the reassessment of previous results and might require a repeated data collection preparation, data collection, simulation and analysis.

### **7.5.3 Analysis limitations**

One of the perceived weaknesses within the research analysis is the need to base the simulation execution and, by this, the analysis on contemporary and fixed parameter values, which constitute the basic assumptions of the research environment. Within the simulation execution these values refer to technical characteristics such as transmission performance and transmission efficiency; within the efficiency evaluation to the cost of electricity per kWh being consumed and the cost of kWh of battery capacity; within the sustainability evaluation to the amount of CO<sub>2</sub> being emitted per kWh of battery capacity as well as the emissions per consumed unit of energy. The technical values are subject to further technological improvements that will change the results in reference to cost and emissions, so that forecasts and projections can increase the informative value for future projections and decrease the need for periodic simulation revisions. Furthermore, national and regional differences impact the generated outcomes as for example energy prices for process powering are subject to local differences and company conditions. The calculations on process-based CO<sub>2</sub> emissions consider an energy mix of generally available energy sources such as coal, gas, oil, wood, renewable energies etc. and are therefore based on average emissions within central European countries. Increased reference to renewable energies or

other low carbon emitting energy sources would affect these values. The reference to fixed basic values restricts the analysis outcome to the assumptions made and therefore to the specific case study, meaning that transfer of results to other cases, i.e. the generalisation of outcomes, is dependent on the choice of assumptions and therefore difficult to achieve. As mentioned in subsection 7.4.3.1, the disposal of batteries before the calculated, nominal battery performance was not explicitly investigated within a separate sensitivity of the analyses. The disposal of batteries before the expected life time will affect the efficiency and ecology outcome. In reference to system sustainability, premature disposal of batteries increases the total cost of system implementation in reference to conventional alternatives, as additional cost occur within the investigation period. In reference to ecology, the earlier replacement increases CO<sub>2</sub> emissions within the defined cycle due to additional battery capacity to be produced. Simulation and tool design allow a more thorough investigation of this case of decreased battery life time within sensitivity analyses. Different life cycle times can be investigated by lowering the full cycle equivalents within the 'vehicle data sheet' (see Appendix D), whereas this was not in the focus of the executed research project.

As highlighted in the literature review, the awareness for the above explained complexity influenced the development of the research method design, meaning that high flexibility in reference to parameter input options were integrated and alternative basic values can be inserted and changed easily. The result is a framework being applicable to most material handling applications and different case study targets, but therefore requires case specific adaptations and simulations under the influence of alternative or changing input parameters.

In reference to the input data within the user interface, information on the number and weight of load carriers is assumed to be based and available on average or estimated values in reference to information and data availability. Owing to the fact that these factors impact the significance of the analysis, the availability and insertion of high quality information is suggested in order to ensure the reliability of results. The deviation of minimal to maximal energy consumption from the median value within the executed restriction of additional payload from 0kg to 1,600kg ranged around 19% of the total process energy consumption, showing the impact from input data (in-)accuracy to the outcome.

The reference to CO<sub>2</sub> emission as a scale of sustainability focuses on the ecology aspect of sustainability in order to evaluate the impact of the technology implementation. This exclusive reference is based on the general focus on CO<sub>2</sub> emissions in public communication, making CO<sub>2</sub> emissions a widely applicable standard of comparison (Kranke, Schmied and Schoen 2011). At this point, it shall be highlighted that additional emissions such as greenhouse gases and nitric oxides (NO) are also emitted within the considered processes, but were neglected as scale of ecology within this research in order to facilitate the evaluation of the results and to maintain the prevalent standard of comparison.

In reference to overall system and process optimisation, it must be admitted that the OCSLM framework and optimisation approach do not include a process routing optimisation. The basic assumption for the design of the optimisation approach considers investigated processes to be either already optimised in reference to driven routes or to be unmodifiable due to the superordinate manufacturing and production processes. This framework design makes the model applicable to existing processes and includes all relevant information on the optimisation execution in reference to charging station allocation for static occasional recharging. For construction design of planned manufacturing lines, subordinate processes are subject to projections, so that the developed framework can be applied for charging station determination or integrated within a Layout Planning model, but does not give general recommendations per se.

As also stated within the weaknesses of data collection and formatting, a prevalent weakness of the OCSLM simulation tool is the requirement of data processing performance and therefore analysis time in order to operate the fundamental simulations including the realisation of idle time calculation and relocation, charging station determination and execution of the impact analyses. The bottle neck functions within the simulation execution are the calculation of idle times, its relocation and charging station location modelling, meaning that the program needs to conduct more than 506,250,000 calculation steps for the simulation of one vehicle data set within a production facility of 150m to 150m in order to consider all possible combinations of cells. Corresponding processing time requirements range from 20 minutes to 30 minutes per each simulation run and by this show the impracticability of a manual calculation, i.e. the need for a dedicated

simulation tool. The execution of a comprehensive case study analysis therefore requires a certain time for processing and evaluation, so that this factor played an essential role within the research project execution. For more complex case studies, the time factor reduces the flexibility of the tool utilisation and needs to be considered within project plan design.

## 7.6 Placement within general context

The executed research and case study on charging station allocation for occasional recharging, and the analysis of the impact from system integration to the system efficiency and sustainability highlighted the complexity of the research environment and the importance of the development of a dedicated investigation framework in order to foster advanced implementation decision making. The results on the case study executions show the influence of a subject specific covering distance in order to integrate process potentials into the charging station allocation decision making. Referring to a mixed, exogenous-endogenous covering distance approach increased the specific demand coverage, i.e. the integration of process immanent process potentials. The migration to a completely endogenous, function-based covering distance leads to a further increase in recharge energy, especially in low potential cases.

As the investigations showed, a sole reference to recharge energy maximisation does not automatically contribute to maximised system adaptations as specific system boundaries constitute adaption limitations that need to be considered within the decision making process. Based on these system and process specific limitations, a subsequent impact analysis has to investigate the influence on increased system efficiency and sustainability.

The cost based efficiency analysis generally showed the highest level of cost saving in reference to the  $E_{ij10}$  and  $E_{ij}$  covering distance, which is majorly based on the low cost of electricity in the investigated research environment. Furthermore, the high cost for lithium ion batteries fosters the profitability of resource savings. In contrast to this, the approaches of  $S_{10}$  and  $E_{ij10}$  showed a preferable, i.e. lower level of  $CO_2$  emissions due to the savings on additional energy efforts and losses in comparison to the  $E_{ij}$  approach, whereas these savings have to be examined in reference to the overall system operation pollutant emissions. The

results on the  $E_{ij10}$  covering distance highlight that this approach presents a compromise solution between cost efficiency and increased sustainability as pollutant emissions are comparable to conventional material handling operations while enabling cost efficient battery downsizing.

In order to foster advanced decision making in electric vehicle material handling operations, decision makers need to be supported by dedicated tools, information and data in order to allow target specific system adaptations. The results of OCSLM and this research project address this need by constituting a dedicated framework that is based on reliable structures and data which is applicable to any investigation case on electric vehicles that focuses on the usage of process immanent potentials. By this, OCSLM addresses several identified shortcomings of existing research and realises previous research recommendations, so that it constitutes a further development within scientific location-allocation modelling.

As the generated results rely on the quality and nature of specific process and component data, the generated results lack direct transferability to other cases, but constitute a starting point for further research and case study investigations in order to increase the interaction and balance of economic and environmental aspects in electric vehicle material handling.

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# CHAPTER 8

## CONCLUSION

### 8.1 Introduction

The target of this concluding chapter lies in the review of the drafted dissertation, and to check the developed and executed contents towards its degree of target achievement in reference to the defined aims and objectives as per section 1.2 [p.6] respectively section 3.3 [p.58]. Furthermore, the innovative character and information of the developed approach as well as its contribution to new knowledge are described and set in context of its research environment. Based on the generated results and the research project review, recommendations for future research work are derived as a concluding remark in Chapter 9.

### 8.2 Research project review

The key target of the pursued research project was to define and develop a framework and method in order to analyse and evaluate the potential of an electrical charging infrastructure for occasional battery charging of battery electric vehicles in production related material handling. Identified key issues referred to the development of a dedicated model for charging station allocation and to analyse and evaluate the impact from charging infrastructure implementation to a system's efficiency and sustainability. The corresponding research aims as well as their realisation are reviewed at this point in order to verify its comprehensive completion:

**(1) Identification and investigation of charging system integration relevant manufacturing process and energy related characteristics and performance indicators of material handling functions**

Relevant key performance indicators in the field of production related material handling have been identified by the first section of the literature review (see sections 2.1 [p.9] to 2.4 [p.26]). In accordance to the explanations of Chow (1990) on assembly line objectives and characteristics, corresponding material handling

processes, components and energy supply systems and its relevant parameters with impact to line performance were investigated in order to serve as decision criteria for location model qualification (section 2.6 [p.33]). Parameter accessibility, availability and relevance were reviewed and discussed with field experts in order to achieve high level information (see also Fekete et al. 2014). Based on the flexible design of OCSLM, investigation parameters can be entered in different quality or average numbers. In line with the SECA approach reference values can be added to the examinations, whereas more accurate numbers increase the investigation's informative value. Due to the dynamics of industrial production and changing conditions in the production arrangement, parameters and parameter values require periodic revision in order to maintain the achieved level of efficiency and to preserve system failures.

## **(2) Provision of a comprehensive understanding about location-allocation models in related fields of charging station positioning through a survey of relevant literature, models and frameworks**

Given that it constitutes a key component of the executed research project, special attention was given to the development and design of a dedicated location-allocation model that integrates and combines the identified parameters such as process structures, sequences, routing, energy consumption and supply figures in reference to system immanent potentials while maintaining the existing level of material handling operation processes. A subsequent aspect to the location modelling is the analysis of the impact from occasional recharging to system efficiency and sustainability, which the location-allocation model needed to address.

Based on the systematic critiquing approach on existing charging station location models, increased understanding on location-allocation modelling was created within the executions of sections 2.5 [p.29] to 2.6 [p.33]. A comprehensive analysis on existing models for charging station allocation and electric vehicle recharging highlighted a total of five models for further review. The comparative model analysis of section 2.7 [p.50] highlighted model specific, beneficial aspects as well as shortcomings towards the application of these models to the research field. Given recommendations supported the development of a specific location-allocation model and resulted in the formulation of the research objectives.



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In completion of the review of the research aims and to investigate on the research hypothesis, the operation and execution of the underlying research objectives is examined below:

**(1) To develop a generally applicable framework for production related material handling that integrates all relevant performance indicators into a specific location-allocation model and that provides recommendation for optimisation approaches**

In reference to the literature review and the derived information the necessity for a dedicated framework that considers all integral research environment components and parameters became apparent. As revealed by the literature review, no model or method was provided that focused on electrical charging station allocation for occasional recharging in industrial application and that included a focus on process structures and potentials. Furthermore, existing approaches neglect detailed information on energy values, so that the development of Standardised Energy Consumption Activities formed the starting point for the design of a dedicated framework. Therefore, OCSLM was designed as a tool being based on standardised information and data on energy values that can be adapted to particular research environments and thus can be used for individual, case specific information generation in order to support case specific decision making. OCSLM generates information on optimised charging station allocation and investigates the impact from charging station allocation to system design, efficiency and sustainability. Referring to OCSLM for allocation optimisation resulted in increased Usable Battery Energy of +40% to +60%. The results underpin the energy improvements based on the developed framework as well as the framework's contribution to new knowledge in the field of charging station allocation for occasional recharging in industrial nrEV applications.

**(2) To integrate technology based characteristics with impact to the performance evaluation**

The literature review on contactless power transfer and corresponding charging stations characteristics generated increased knowledge on technology performance indicators and pointed out reference values (subsection 2.3.3.3 [p.24]). Battery specific impact factors with relevance to the system's energy balance were reviewed in subsection 2.3.3.2 [p.22]. Besides of these energy supply based

aspects, energy consumption investigations focused on the generation of reliable and accurate data. The executions of section 4.2 [p.89] describe the approach taken in order to collect material handling, technology specific consumption data with applicability to changed technical specifications in order to address the requirements of objective (2). The combination with detailed process information as per section 4.3 [p.100] increased the accuracy of the investigation results.

All described factors were integrated into the design and development of the location-allocation model.

### **(3) To integrate lean and green aspects of the technology implementation**

In a first examination, the definitions of Lean and Green as well as their core aspects and implications for the pursued research project were introduced by the explanations of section 2.2 [p.11]. Following to these definitions, the analyses of the research project with the target to investigate the impact from the technology implementation to the Lean parameter cost and the Green parameters resource usage and CO<sub>2</sub> emissions were evaluated based on a quantitative optimal model design. The Lean aspect as being the minimisation of waste and resource input with the target to result in decreased cost was especially integrated within the analysis design of chapter 5 [p.105] and the efficiency investigations of subsection 7.4.3.1 [p.184]. Addressing the demand for increased sustainability, i.e. ecology, (Pampanelli, Found and Bernardes 2013), reference was taken by the integration of resource savings in reference to battery capacity saving as well as CO<sub>2</sub> emission investigations. These investigations considered technology based CO<sub>2</sub> savings by battery downsizing in comparison to additional efforts caused by efficiency and process constraints (see subsection 5.3.3 [p.138]).

### **(4) To execute case study based performance analyses to foster understanding of CPT operations, cost-benefits and performance trade-offs**

The findings and interim results of the literature review and data collection were used to perform case study investigations based on the developed simulation tool OCSLM (chapter 6 [p.144]). The results of the charging station location optimisation with focus to charging energy maximisation were reviewed and used within subsequent impact analyses (subsections 6.3.3 [p.154]/ 6.4.3 [p.161]/ 6.5.3 [p.166]). From the investigations on recharge energy maximisation and the oper-

ated impact analyses, further implications on the efficiency, i.e. cost based investigation, and the sustainability, i.e. ecology based investigation, were deduced in order to allow the evaluation of the charging system implementation in reference to efficiency and sustainability.

#### **(5) To evaluate the potentials of occasional charging for increased system efficiency and sustainability**

By the concept of integrating more detailed energy data to the investigations in reference to consumption, supply and losses based on different covering distance definitions, OCSLM provides the possibility to compare alternatives of charging station allocation approaches (see executions of chapter 6 [p.144]). On the basis of the simulation results, the impact of these approaches, i.e. the integration of an occasional charging infrastructure, to efficiency and sustainability were determined and evaluated (subsection 7.4.3 [p.183]). In line with the specific target definition in reference to efficiency and/or sustainability, corresponding conclusions and measures were derived (section 7.5 [p.188]) in order to address the hypothesis that ‘the process-based integration of contactless power transfer systems for occasional recharging of industrial truck batteries in optimised location(s) creates the potential for increased efficient and sustainable system solutions’. The investigations showed increased efficiency and an economic integrability of occasional, contactless charging systems whereas the system technology characteristics prevents this integration from being ecologically sound as a scale of sustainability.

### **8.3 Contribution to knowledge**

As transpired in the literature review, several approaches for refuelling station and electric charging station allocation have been introduced in the past, whereas these approaches, being developed for road electric vehicles, base charging station allocation on maximal coverage being represented by its geographic appearance and without reference to a specified quantity of demand. Within the executed literature review, process performance indicators with relevance to energy consumption and supply were identified and put in context to charging station allocation on occasional recharging in industrial material handling. In doing so, pre-existing knowledge on material handling processes and energy consumption

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was reviewed in reference to battery charging technology improvements so as to define the components in this new field of research.

The lack of an available, general comparison standard in the field of material handling energy consumption was detected throughout the literature review, so that the development of a specific and precise value benchmark presents a milestone within electric vehicle operations. The reference to Standardised Energy Consumption Activities is based on minimal process functions to be executed and monitored in reference to their individual energy consumption. The SECA values are subject to be used and combined within the investigation, simulation or design of more complex process structures, so that they are easy to generate and easy to use. The SECA approach presents the first of its kind within electric mobility and transportation with a high precision on its values and its standard being applicable to any material handling or transportation process being based on electric energy engines.

Following on from this, the comparison of existing approaches for electric charging station allocation, the critique on individual advantages and disadvantages for application in a nrEV environment, as well as the deduction of model specific aspects with importance to the development of a dedicated framework and simulation model contributed to the generation of new knowledge in the field of charging station allocation. Subsequent to the determination of shortcomings and requirements, the Excel-based tool OCSLM and its dedicated framework has been developed as part of the research project being a valuable extension of the existing models and procedures.

The OCSLM approach constitutes the first investigation that considers occurrence, frequency and duration of process immanent idle times, as well as process characteristics and corresponding energy data by integrating these parameters as potentials for electric vehicle recharging within a continuous charging station allocation model. Furthermore, the executed research project is the first scientific investigation that deals with process integration of contactless charging systems for occasional recharging as a special type of electric vehicle recharging.

The application of the OCSLM approach and the integrated covering distance definitions within the given case study showed a positive impact to the availability of recharge energy for increased UBE. The target of increased efficiency was

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achieved by the integration of recharging sequences within the existing process sequences by changing economically unused idle times for system perpetuation. This model of potential evaluation is unique within the scientific landscape, as it is the first to consider charging times as process inherent efforts to be taken instead of evaluating charging times, i.e. demand satisfaction, to be available upon demand.

The results of the pursued investigations that contain information and properties as contribution to new knowledge emerge from several of the OCSLM framework steps such as the setup and the processing phase. Important components and information emerge from the design and the execution of the framework, and the development of Standardised Energy Consumption Activities for production related material handling; the development of a MCLM based algorithm for occasional charging station allocation and its inherent combination of process and energy data under the integration of a new, endogenous function for covering distance determination; the comparative analysis of exogenous and endogenous, respectively a combined covering distance approach and the integration into the subsequent impact analysis; the investigation on the self-reinforcing degradation effect of battery downsizing to the impact analysis which turned out to be of minor importance in this application; and the realisation of the above mentioned elements into a comprehensive framework for system simulation and impact analysis.

Additionally, an important advantage of OCSLM lies in its general applicability to individual environmental needs and requirements in order to cope with the fact that production facilities as well as deployed material handling equipment and processes are industry, company and case specific. The generic design of OCSLM allows its use within multiple investigation environments with the possibility to simulate multiple sensitivities for occasional charging. Therefore, OCSLM can also be used to investigate contact based charging within an occasional charging application besides of the contactless alternative of this research project. In reference to the availability of fast connecting charging systems for contact charging (see subsection 2.3.3.3 [p.24]), OCSLM as a tool as well as its structure, values and results on occasional charging can be transferred to this charging

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topology with the only need to adapt the information on the performance and efficiency of the energy transmission within the input part of OCSLM (see section 5.3 [p.126]). The operation of an OCSLM based optimisation for contact based, occasional charging showed improved values within the ecology investigation, so that technology based CO<sub>2</sub> emissions decrease to 6.24% of the total process CO<sub>2</sub> emissions, i.e. -0.94% of the emissions in reference to conventional charging.

The impact from the case selection was revealed in the case study execution that highlighted day to day differences even within single sub-cases in reference to process sequences and routing. The application of OCSLM in alternative environments requires the digital design of the investigated warehouse, so that this effort needs to be considered for its application. The time being required for this depends on the structure and complexity of the warehouse, whereas only inner structures such as shelves, racks and inner walls need to be designed (see 5.3.1.2 [p.128]). As previously discussed, the nature and structure of processes determine the individual conditions and requirements to the material handling equipment, meaning that alternating conditions significantly modify the outcome. Long term analyses can produce extreme conditions as bottle neck cases for system adaptations in order to avoid system shortages, whereas safety arrangements are subject to integration.

From the research project executions and results, it can be derived that the developed framework provides a valuable and novel source of information in the field of electric charging station allocation in manufacturing related material handling. The subsequent structure for the execution of a subject specific impact analysis on system efficiency and sustainability based on the results of the Occasional Charging Station Location Model can be considered as a new and essential contribution to knowledge in this field.

## CHAPTER 9

### RECOMMENDATION FOR FUTURE RESEARCH

The presented research project constitutes a comprehensive analysis within the field of electric vehicle charging and electric charging station allocation. From the research executions, increased knowledge on the parameters and alternatives of electric charging station allocation were derived that are essential components for the technology implementation evaluation. The focus of this research project lies in the development of a dedicated framework that considers all impact parameters and factors in respect to system energy supply and its physical allocation. In doing so, the approach to potential evaluation of contactless energy supply infrastructure for occasional recharging in production related, non-automated material handling constitutes as starting point for future research in this field. As mentioned in section 5.2 [p.106], OCSLM constitutes an incapacitated model for charging station allocation, meaning that unavailability of charging stations due to congestion is disregarded. Applying OCSLM to more complex fleet investigations, i.e. a larger number of considered vehicles, will have to integrate this factor in order to achieve a high level of efficiency at constant vehicle availability. Furthermore, the executed investigations assumed process vehicle routing to be optimised towards assembly line requirements, meaning that vehicle battery recharging is operated in process immanent idle times only under the acceptance of additional vehicle movements. In a subsequent approach, the idle times considered by OCSLM can also be integrated into a routing optimisation algorithm, in order to minimise the additional drive distances for charging station approaching and to more efficiently integrate charging times while changing its categorisation from inefficient sequence components to process immanent sequences.

Another open field for future research is the execution of further investigations on material handling vehicles, charging station allocation and optimisation based on OCSLM in similar and alternative research environments, such as logistics distribution centres or warehouses, in order to expand the knowledge on material handling processes, structures and related energy consumption. A total of 11% of CO<sub>2</sub> emissions is related to transportation and storage activities within distribution

centres (Eurostat 2014), so that the application of occasional charging in distribution centre environments in addition to production related material handling (see also subsection 1.1 [p.2]) would increase the impact from technology implementation to total CO<sub>2</sub> emissions and should therefore be subject to more thorough investigations in reference to its transmission efficiency.

The execution of these investigations will foster the need for increased information and data in reference to energy consumption such as SECA, but also make it available. An increased number of case studies on charging station allocation for occasional recharging needs to investigate and compare the results as well as to examine structural and design patterns in order to induce research generalisations.

In addition to case and process specific figures and numbers, simulations and calculations of the executed research investigations are based on general assumptions with regional or technological reference such as cost of electricity, battery production based CO<sub>2</sub> emissions, the number of battery full cycle equivalents as well as battery cost etc., meaning that the generated results prevent general conclusions in reference to efficiency and sustainability. Adjacent investigations have to change the research settings to different global regions with different cost of energy, alternative battery technology solutions with the target to increase battery life time as well as examine the impact from early disposal of batteries for example due to damages or increased alteration in order to increase knowledge in this field and to develop further reference models.

In conjunction with the results of this research project on system efficiency, but especially on sustainability, the importance of increasing power transmission efficiency of occasional recharging by different technical approaches needs to be highlighted. The amount of additional losses resulting from increased transmission losses of contactless recharging was identified as a core impact parameter on the reduced sustainability of this type of occasional recharging, whereas other technologies for occasional recharging such a fast-plug solutions or sliding contact alternatives may be considered within tied up investigations.



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**APPENDIX**

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## **Appendix A - Explanations on Location Theory**

Economic location theories focus on localisation patterns and developments of localisation(s) in the two-dimensional space. Derived from these developments, approaches try to develop and deduce statements and predictions about future developments within the defined market in order to explain and optimise the forecasted events (Church and ReVelle 1974).

The target of layout planning is the spatial location of production facilities in order to adapt the organisation of operating resources according to the production processes and sequences (ReVelle and Eiselt 2005). Charging station allocation is no part of the manufacturing process as recharging represents an auxiliary function in production. The integration of charging station allocation in layout planning is executed in automated guided processes where projectable process interruptions for interim charging can be used. The implementation of a charging infrastructure for occasional recharging in non-automated and therefore non-projectable processes lacks the applicability of layout planning as the model needs to optimise the system allocation based on process structures of auxiliary material supply functions. As material supply functions are operated on on-demand basis and by this depend on market order characteristics, the requirements to the developed allocation model is increased flexibility in order to increase analysis adaptability to alternating supply processes and to analyse the potentials of occasional recharging.

Facility location models possess a higher degree of flexibility as these employ several variable components for the characterisation of the investigated location problem, so that economic location theories as well as layout planning are excluded from further considerations.

### **Facility Location Planning**

Facility location models refer to the combination of (1) demand (= customers), which is assumed to be located at defined points or on routes, (2) supply (= fixed or variable number of facilities), to be allocated, (3) defined space and, (4) a metric representation in order to define times and distances from/to supply to/from demand (ReVelle and Eiselt 2005).

The spatial arrangement of facilities is determined by the demand and the way of assignation of it. According to Drezner and Eiselt (2002: 151) Location Choice

models allow to dedicate demand locations and the inherent value of demand without the reference to economic or process related rules. Subsequently, the dedication of demand is based on a probabilistic distribution. Location-Allocation models are based on defined decision rules, meaning that demand is dedicated to supply accordingly. As the demand in the field of occasional recharging is, amongst other things, represented by the number and volume of break times that are subject to be used for additional recharging in order to increase UBE, the attribution follows the location-allocation approach.

Having identified location-allocation models as preferable models for occasional charging station allocation, the subsequent section elucidates and defines the core characteristic of median, hub and covering models. The specifications of these models determine the location algorithm of the allocation approach so that the choice of model influences and determines the geographic and relative location.

### **Median Models**

Many location-allocation models refer to the distance between the location of demand and supply as being the dimension unit for efficiency. This implies that supply stations with minimal distance to the demand spots are favourable over the ones of higher distance.

In dependence on the definition of Hakimi (1965), the existing demand is assumed to be distributed on  $R$  different locations, whereas  $b_r$  represents the demand in the location  $r$ .  $J$  defines the number of possible locations of facilities and by this defines the model as a discrete solution.  $s$  with  $s < |J|$  defines the number of facilities/stations to be implemented. The distance between the demand spot  $r$  and facility allocation spot  $j$  is named  $d_{rj}$ . The median of these relations is the minimum sum of the weighted, shortest distance(s) between the nodes of  $r$  and the nodes of  $j$ . The weighting factor is defined by the demand.

The position of a facility is based on the binary variable  $y_j$  (see equation 57 and 60). Equally the binary variable  $x_{rj}$  determines the attribution of a demand spot  $r$  to the facility  $j$ . As per equation (56), the target of median models is to determine facility allocation(s) by minimising the total weighted distance of demand spots to the defined number of facilities  $s$ :

$$\min \sum_{r \in R} \sum_{j \in J} b_r d_{rj} x_{rj} \quad (56)$$

s.c.

$$\sum_{j \in J} y_j = s \quad (57)$$

$$\sum_{j \in J} x_{rj} = 1 \quad \forall r \in R \quad (58)$$

$$x_{rj} - y_j \leq 0 \quad \forall r \in R, j \in J \quad (59)$$

$$y_j = (0,1) \quad \forall j \in J \quad (60)$$

$$x_{rj} = (0,1) \quad \forall r \in R, j \in J \quad (61)$$

The side condition (57) defines the number of stations to be allocated to be  $s$ . (58) assures the affiliation of exactly one station to each demand spot, whereas (59) prevents the affiliation of demand to a spot of no coverage. (60) and (61) define the values of  $y_j$  and  $x_{rj}$  to be whether 1 or 0 according to the aforementioned events.

### Hub Models

Hub models target to most centrally allocate a facility or facilities within the defined cover area in reference to a defined demand. In respect to the defined target this central allocation searches for the maximal, but still most central, or minimal, but still most central, distant allocation. The dimension unit for the determination of efficiency is the fraction of demand to be covered.

Choosing a discrete distribution of facilities/supply sites refers to the so called Vertex-Hub-Models; continuous distribution refers to Absolute-Hub-Models. Hub models first identify the most central spots with maximum distance  $a'$  of demand and supply which then is minimised according to the target definition. Demand can be covered by one or more facilities which is affiliated to the closest or most distant facility.

According to Owen and Daskin (1998) a Vertex-Multi-Hub-Model can be defined as:

$$\min a' \quad (62)$$

s.c.

$$\sum_{j \in J} y_j = s \quad (63)$$

$$\sum_{j \in J} x_{rj} = 1 \quad \forall r \in R \quad (64)$$

$$x_{rj} - y_j \leq 0 \quad \forall r \in R, j \in J \quad (65)$$

$$a' \geq \sum_{j \in J} x_{rj} d_{rj} \quad \forall r \in R \quad (66)$$

$$y_j = (0,1) \quad \forall j \in J \quad (67)$$

$$x_{rj} = (0,1) \quad \forall r \in R, j \in J \quad (68)$$

The target function (62) minimises the distance in reference to all demand spots. The side condition (63) defines the number of stations to be allocated to be  $s$ . (64) assures the affiliation of exactly one station to each demand spot, whereas (65) prevents the affiliation of demand to a spot of no coverage. Equation (66) defines the maximum distance from demand point  $r$  to supply allocation  $j$ , whereas there is no qualitative definition for the evaluation of this distance. (67) and (68) define the values of  $y_j$  and  $x_{rj}$  to be whether 1 or 0 according to the above defined events.

As per the above explanations, hub models integrate a first aspect of economy to the location-allocation investigations as it defines the travel distance from  $r$  to  $j$  to be minimised.

### Covering Models

Covering Models increase the flexibility, i.e. adaptability of location-allocation models by specifically considering individual demand spots. The minimisation of travel distance is replaced by the consideration of a maximum distance, which enables the definition of a range for individual demand to be covered by a single facility. The evaluation of individual facilities is based on the coverage of demand spots and demand itself, not on minimised distances, meaning that this approach

optimises the location of a facility in reference to the specified target. This definition of a target specific covering location is the reason for the design and reference of the pursued research project according to the covering model approach. Being based on the ratio of coverage, Covering Models are differentiated into Location-Set-Covering-Models (LSCM) and Maximal-Covering-Location-Models (MCLM).

### Location Set Covering Model

LSC-Models target on the total coverage of demand within a defined area of investigation. The number of stations depends on the defined maximal distance, i.e. maximal travel time from demand to supply. The focus of LSCM lies on the minimisation of cost for infrastructure in reference to total coverage.

The largest acceptable distance, respectively time, from demand to supply is defined as 'covering distance', respectively 'covering time',  $a$ .  $X_r$  with  $X_r = \{j \mid d_{rj} \leq a\}$  defines the number of facilities that cover the demand in demand spot  $r$  that are located within the covering distance  $a$ . Marianov and Serra (2002) defined the LSC-problem as per the equations below:

$$\min \sum_{j \in J} y_j \quad (69)$$

s.c.

$$\sum_{j \in J} y_j \geq 1 \quad \forall r \in R \quad (70)$$

$$y_j = (0,1) \quad \forall j \in J \quad (71)$$

The target function (69) minimises the number of required facilities for total coverage. (70) assures that every demand spot is served by a facility within covering distance  $a$ . (71) defines the binary character of the variables.

## Appendix B - Exemplary Forklift Truck Data Sheet

### Linde E16P

#### Technical data

		Model group	E 16	
Distinguishing mark	1.1	Manufacturer (abbreviation)	LINDE	
	1.2	Manufacturer's type designation	E 16	
	1.3	Drive: electric (battery or mains), diesel, petrol, fuel gas	Battery	
	1.4	Operator type: hand, pedestrian, standing, seated, order-picker	Seated	
	1.5	Load capacity/rated load	Q (t)	1.6
	1.6	Load centre distance	c (mm)	500
	1.8	Load distance, centre of drive axle to fork	x (mm)	365
	1.9	Wheelbase	y (mm)	1301 <sup>1)</sup>
	Weight	2.1	Service weight	kg
2.2		Axle loading, laden front/rear	kg	4100/595
2.3		Axle loading, unladen front/rear	kg	1435/1660
Tyres, chassis	3.1	Tyres: solid rubber, superelastic, pneumatic, polyurethane	SE	
	3.2	Tyre size, front	18 x 7 - 8 <sup>2)</sup>	
	3.3	Tyre size, rear	15 x 4 1/2 - 8 <sup>3)</sup>	
	3.5	Wheels, number front rear (x = driven wheels)	2x/2	
	3.6	Tread, front	b10 (mm)	930
	3.7	Tread, rear	b11 (mm)	168
	Dimensions	4.1	Tilt of mast/fork carriage forward/backward	Grad
4.2		Height, mast lowered	h1 (mm)	2019 <sup>4)</sup>
4.3		Free lift	h2 (mm)	150
4.4		Lift	h3 (mm)	2800
4.5		Height, mast extended	h4 (mm)	3401
4.7		Height of overhead guard (cabin)	h6 (mm)	1970
4.8		Seat height/stand height	h7 (mm)	908
4.12		Coupling height	h10 (mm)	510
4.19		Overall length	l1 (mm)	2766
4.20		Length to face of forks	l2 (mm)	1866
4.21		Overall width	b1/b2 (mm)	1090/1050 <sup>7)</sup>
4.22		Fork dimensions	s/e/l (mm)	40 x 80 x 900
4.23		Fork carriage DIN 15173, class/type A, B		2A
4.24		Fork-carriage width	b3 (mm)	1040
4.31		Ground clearance, laden, below mast	m1 (mm)	89
4.32		Ground clearance, centre of wheelbase	m2 (mm)	96
4.33		Aisle width for pallets 1000 x 1200 crossways	Ast (mm)	3196
4.34		Aisle width for pallets 800 x 1200 lengthways	Ast (mm)	3320
4.35		Turning radius	Wa (mm)	1505
Performance data		4.36	Internal turning radius	b13 (mm)
	5.1	Travel speed, laden/unladen	km/h	16/16
	5.2	Lift speed, laden/unladen	m/s	0.4/0.6
	5.3	Lowering speed, laden/unladen	m/s	0.58/0.47
	5.5	Drawbar pull, laden/unladen	N	2300/2300
	5.6	Max. drawbar pull, laden/unladen	N	9200/9200
	5.7	Gradeability, laden/unladen	%	6.7/10.3
	5.8	Max. gradeability, laden/unladen	%	20.6/32.3
	5.9	Acceleration time, laden/unladen	s	4.5/4.0
	5.10	Service brake		hydr./mech.
Electric engine	6.1	Drive motor rating S2 60 min	kW	2 x 4.6
	6.2	Lift motor rating at S3 15%	kW	10
	6.3	Battery acc. to DIN 43531/35/36 A, B, C, no		43531A
	6.4	Battery voltage, nominal capacity K <sub>5</sub>	V/Ah	48/440 (460) <sup>9)</sup>
	6.5	Battery weight	kg	708
	6.6	Energy consumption acc. to VDI cycle	kWh/h	6.4
Addition data	8.2	Operating pressure for attachments	bar	170
	8.3	Oil volume for attachments	l/min	32 <sup>8)</sup>
	8.4	Sound level at the driver's ear according to DIN 12053	dB(A)	< 65
	8.5	Towing coupling, type DIN		-

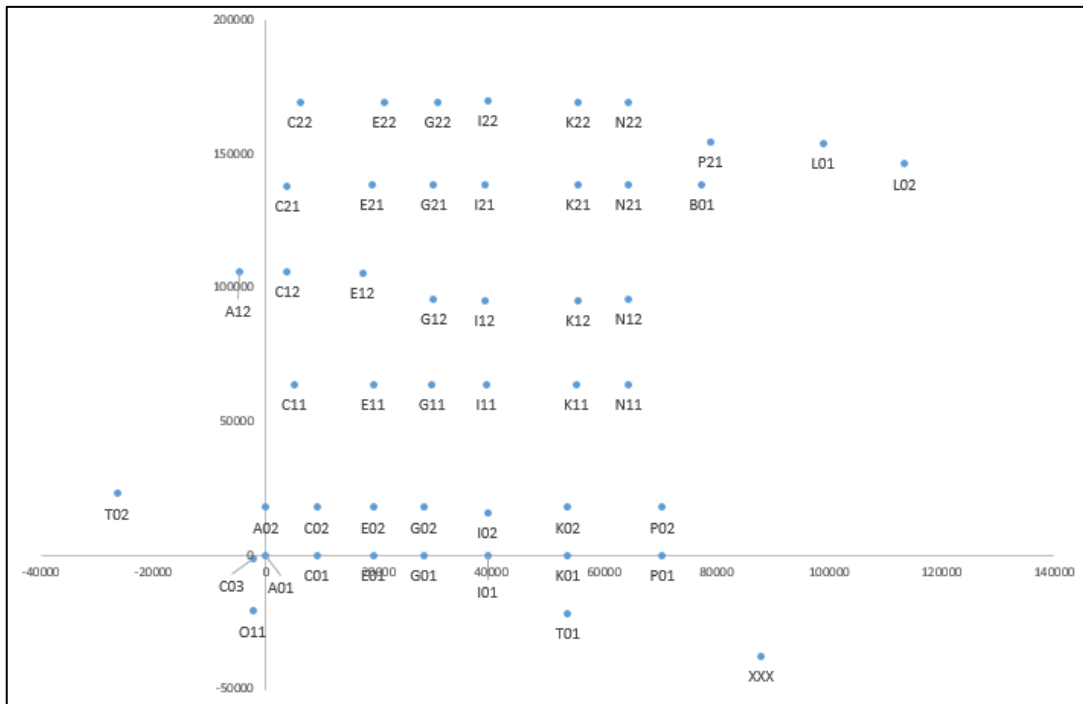
<sup>1)</sup> With lifting mast vertical  
<sup>2)</sup> Optional: pneumatic tyres, 18x7-8 7 16PR or wrap-around  
<sup>3)</sup> Optional: pneumatic tyres, 15x4 1/2-8/12PR  
<sup>4)</sup> Optional: pneumatic tyres, 16x6-8/14PR

<sup>5)</sup> optional: wrap-around tyres  
<sup>6)</sup> With 150 mm free lift  
<sup>7)</sup> With wrap-around tyre, 18x6 b1-1074  
<sup>8)</sup> At 80% nominal pressure (8.2)

<sup>9)</sup> Data between brackets are taken from the ZVEI instruction leaflet on "Use of European-series cells in DIN-standard batteries" (July 2002 edition).

According to VDI 2198

Appendix C - Exemplary marker file



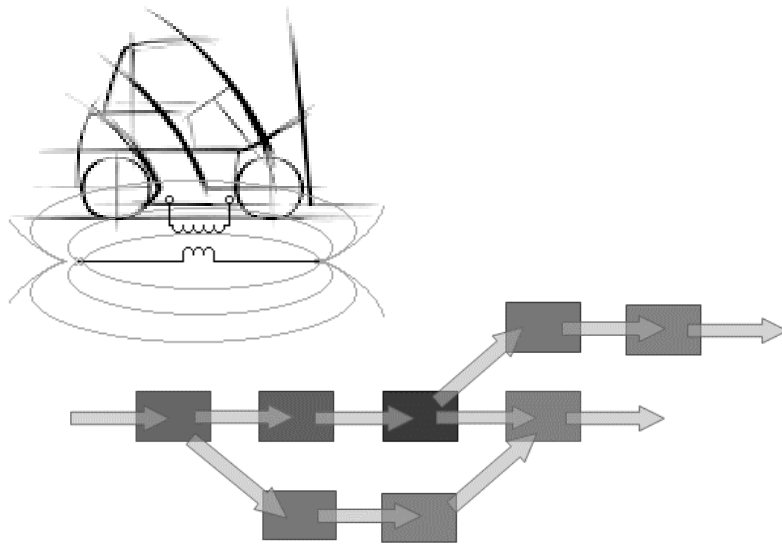


Appendix D - OCSLM User Manual

# User Manual

## OCSLM

Occasional Charging Station Location Model



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## Content

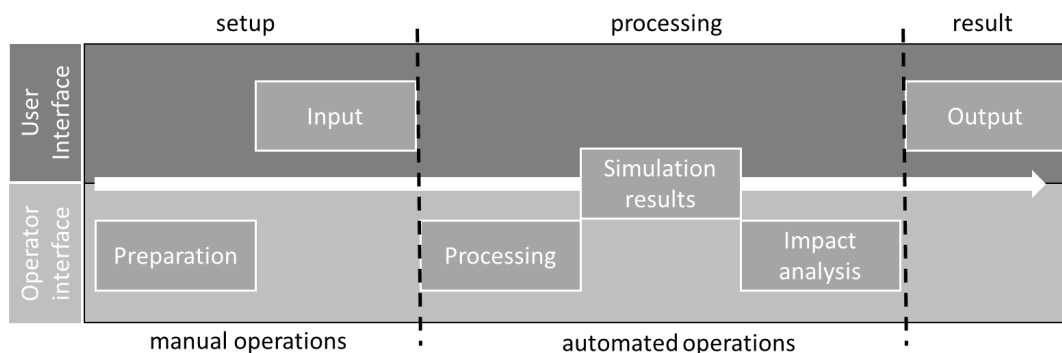
<b>Purpose</b> .....	1
<b>Structure</b> .....	1
<b>OCSLM Macros</b> .....	1
<b>Types of Macros</b> .....	1
<b>Setup to Macro execution</b> .....	2
<b>Macro 1 – Auswertung/data analysis</b> .....	4
<b>Macro 2 – Hilfsmatrix/auxiliary matrix</b> .....	6
<b>Macro 3 - Matrix kombinieren/combination of matrices</b> .....	7
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<b>Macro 6 - Auswirkungen pro Fahrzeug/impact analysis</b> .....	12

## 1. Purpose

OCSLM was developed as a tool to simulate production related material handling processes in order to identify optimized production process integrated charging station allocations for occasional recharging. Impacts to system energy balance and material handling system design can be evaluated on OCSLM results.

## 2. Structure

For easy user application, OCSLM is divided into three subsequent analytic parts such as setup, processing and result part. The general simulation and analysis setup is executed on the operator level, so that the user is enabled to easily enter case specific information and to change inputs for the realization of comprehensive analyses. Simulation results include information on optimized charging station allocation as well as energy results on process level. The impact analysis transforms this information in number based decision recommendations being presented within the output worksheet.



For indeed understanding, the following chapters explain the realization of OCSLM based on Microsoft Excel Visual Basic for Applications.

## 3. OCSLM Macros

A Microsoft Office Macro is defined as a Visual Basic for Applications (VBA) code saved inside a document. Macros are highly efficient tools which can perform multiple operations in a fraction of a second. This tool will save time by avoiding repetitive work.

OCSLM uses six different types of Macros which are used to identify optimized charging station allocations, with the target to evaluate the process-based performance of occasional recharging systems.

## 4. Types of Macros

- Macro 1 – Auswertung/data analysis
- Macro 2 – Hilfsmatrix/auxiliary matrix
- Macro 3 - Matrix kombinieren/combination of matrices
- Macro 4 – Energie/energy
- Macro 5 – Info

- Macro 6 - Auswirkungen pro Fahrzeug/impact analysis

These macros will evaluate the number of break time, rechargeable energy and duration of halts.

## 5. Setup to Macro execution

The Setup phase is executed within the operator interface in order to prepare the analysis execution. Therefore, the OCSLM operator inserts process data including process routing and sequencing, process times, etc. as per the below illustrated steps.

- Select the values of 'X' and 'Y' co-ordinate position from raw data sheet.

	POSITION X	POSITION Y	POSITION Z	ORIENTATIO
'X' Co-ordinate	53185	168732	2148	177.63
	52307	168858	2173	182.04
	51416	168913	2165	186.07
	50521	168880	2165	188.46
	49549	168797	2165	189.38
	48674	168701	2165	189.83
	47749	168574	2165	188.89
	46904	168465	2165	186.85
	46013	168379	2165	184.59
	45217	168326	2165	182.76
	44379	168301	2165	180.67
	43610	168326	2165	178.41
	42783	168368	2165	176.34
	41998	168436	2165	175.02
	41111	168538	2165	174.49

'Y' Co-ordinate

- Insert the selected values of 'X' and 'Y' values based on metres in respective fork-lift data files.

Date	Time	POSITION X	POSITION Y	Speed	LOADED	Drain	SoC
Fzg3_T2	00:00:00,500	52.685	169.076	2.40	1	0.00	26.00
Fzg3_T2	00:00:01,000	51.477	169.242	2.37	1	0.00	26.00
Fzg3_T2	00:00:01,500	50.294	169.273	2.18	1	0.00	26.00
Fzg3_T2	00:00:02,000	49.206	169.257	2.14	1	0.00	26.00
Fzg3_T2	00:00:02,500	48.135	169.224	1.96	1	0.00	26.00
Fzg3_T2	00:00:03,000	47.157	169.181	2.14	1	0.00	26.00
Fzg3_T2	00:00:03,500	46.087	169.128	2.01	1	0.00	26.00
Fzg3_T2	00:00:04,000	45.083	169.094	2.15	1	0.00	26.00
Fzg3_T2	00:00:04,500	44.01	169.065	2.10	1	0.00	26.00
Fzg3_T2	00:00:05,000	42.961	169.034	2.49	1	0.00	26.00
Fzg3_T2	00:00:05,500	41.716	168.999	2.45	1	0.00	26.00
Fzg3_T2	00:00:06,000	40.492	168.985	2.71	1	0.00	26.00
Fzg3_T2	00:00:06,500	39.136	168.987	2.66	1	0.00	25.95
Fzg3_T2	00:00:07,000	37.872	169.397	2.73	1	0.00	25.95
Fzg3_T2	00:00:07,500	36.507	169.441	2.52	1	0.00	25.95
Fzg3_T2	00:00:08,000	35.248	169.467	2.42	1	0.00	25.95
Fzg3_T2	00:00:08,500	34.036	169.464	2.39	1	0.00	25.95

New 'X' Co-ordinate

New 'Y' Co-ordinate

- Select the values of 'Valid' from raw data sheet.

	DISTANCE	LOADED	VALID	L
Valid	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
	-96	1	1	1
-96	1	1	1	

- Add selected values of 'Valid' in 'loaded' column in respective forklift sheet.

	POSITIONY	Speed	LOADED	Drain	SoC
Loaded	169.076	2.40	1	0.00	26.00
	169.242	2.37	1	0.00	26.00
	169.273	2.18	1	0.00	26.00
	169.257	2.14	1	0.00	26.00
	169.224	1.96	1	0.00	26.00
	169.181	2.14	1	0.00	26.00
	169.128	2.01	1	0.00	26.00
	169.094	2.15	1	0.00	26.00
	169.065	2.10	1	0.00	26.00
	169.034	2.49	1	0.00	26.00
	168.999	2.45	1	0.00	26.00
	168.985	2.71	1	0.00	26.00
	168.987	2.68	1	0.00	26.00

After having entered the case specific process data, run the Macros in order to execute the OCSLM analysis. The function of all Macros listed above are explained in detail in following session.

## Macro 1 – Auswertung/data analysis

Macro 1 Auswertung/data analysis evaluates all parameters of forklifts during its operation. Add 'X' and 'Y' co-ordinates of forklifts. Also put values of 'Void' column in 'Loaded' column. Then run macro 1 Auswertung/data analysis.

The generated results includes following data in tabular format.

- Velocity at particular (X, Y) position of forklift at particular instance
- Battery status at particular (X,Y) position of forklift
- Total distance covered during working period
- Total brake time during working period

Besides this it will also generate the number of halts and duration of each halt in matrix format.

This analysis is used to calculate the velocity of a vehicle at given co-ordinates. Energy is defined to be consumed when a vehicle is in motion. If a vehicle stops at a particular point or if it remains idle, then energy consumption is considered as being zero.

Steps to operate Macro #1.

1) Go to 'Data' sheet

2) Click Tab 'Macros'

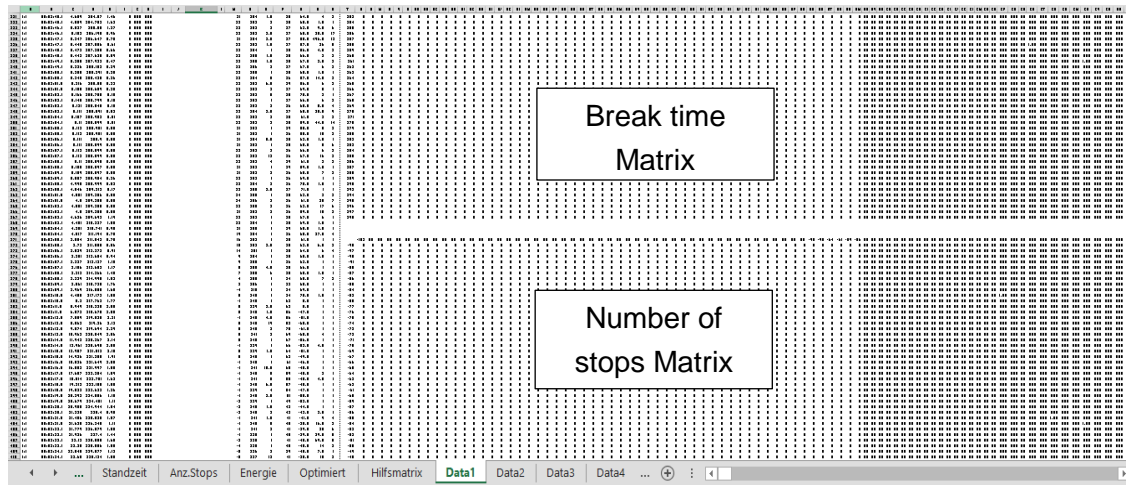
3) Select Macro name 'Auswertung'

4) Click on 'Run'

The screenshot shows the 'Macros' dialog box with the following details:

- Macro name: Makro1\_Auswertung
- Macro names in list: Makro1\_Auswertung, Makro2\_Hilfsmatrix, Makro3\_Matrix\_kombinieren, Makro4\_Energie, Makro5\_Info, Makro6\_AuswirkungProFahrzeug
- Buttons: Edit, Create, Delete, Options..., Cancel
- Macros in: All Open Workbooks
- Description: Ausführen im Reiter "DataX"

Macro # 1 generates two matrices. The top matrix shows the volume of break times in reference to its occurrence in X- and Y-coordinates. The bottom matrix shows the number of stops that contribute to the total break time duration.



In a second step the Macro calculates the vehicle velocity and state of charging at particular locations including start and end point of work.

	A	B	C	D	E	F	G	H	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH										
1	Date	Time	POSITIONX	POSITIONY	Speed	LOADED	Drain	SoC	Gesamtpausenzeit	X-Koord	Y-Koord	Duration	XH-Koord	YH-Koord	Duration	Quantity		-19	-15	-14	-13	-12	-11	-3	-2	1	2	3	4	5	6											
2	Ffg3_T2	00:00:00.500	52.665	163.076	2.40	1	0.00	26.00	27677.00 s	20	181	1.5	20	181.0	2.5	2		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0									
3	Ffg3_T2	00:00:01.000	51.477	163.242	2.37	1	0.00	26.00	461.28 min	20	182	2	20	182.0	2	1		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0								
4	Ffg3_T2	00:00:01.500	50.294	163.273	2.18	1	0.00	26.00	7.63 h	20	183	32	20	183.0	32	1		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
5	Ffg3_T2	00:00:02.000	49.206	163.257	2.14	1	0.00	26.00	Gesamtzeit	20	184	1	20	184.0	1	1		5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						
6	Ffg3_T2	00:00:02.500	48.135	163.224	1.96	1	0.00	26.00	28895.50 s	20	187	1	20	187.0	1	1		6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
7	Ffg3_T2	00:00:03.000	47.157	163.181	2.14	1	0.00	26.00	461.45 min	19	188	3.5	19	188.0	3.5	1		9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	Ffg3_T2	00:00:03.500	46.067	163.120	2.01	1	0.00	26.00	9.02 h	19	189	15.5	19	189.0	15.5	1		26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
9	Ffg3_T2	00:00:04.000	45.083	163.094	2.15	1	0.00	26.00	Gesamtstrecke	19	191	5	19	191.0	5	1		54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
10	Ffg3_T2	00:00:04.500	44.01	163.065	2.10	1	0.00	26.00	1208.50 s	19	192	1	19	192.0	1	1		55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
11	Ffg3_T2	00:00:05.000	42.961	163.034	2.49	1	0.00	26.00	20.14 min	19	194	1	19	194.0	1	1		56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
12	Ffg3_T2	00:00:05.500	41.716	163.399	2.45	1	0.00	26.00	0.34 h	12	198	1	12	198.0	1	1		57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13	Ffg3_T2	00:00:06.000	40.492	168.385	2.71	1	0.00	26.00	Gesamtstrecke	9	198	1	9	198.0	1	1		59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	Ffg3_T2	00:00:06.500	39.136	168.387	2.66	1	0.00	25.99	618.87 m	7	199	1	7	199.0	1	1		62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
15	Ffg3_T2	00:00:07.000	37.872	163.397	2.73	1	0.00	25.99	0.82 km	6	199	1	6	199.0	1	1		64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	Ffg3_T2	00:00:07.500	36.507	163.441	2.52	1	0.00	25.99		5	199	1	5	199.0	1	1		65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Ffg3_T2	00:00:08.000	35.248	163.467	2.42	1	0.00	25.99		5	200	1	5	200.0	1	1		66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Ffg3_T2	00:00:08.500	34.036	163.464	2.39	1	0.00	25.99		4	200	6	4	200.0	6	1		67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	Ffg3_T2	00:00:09.000	32.84	163.448	2.51	1	0.00	25.99		3	206	1	3	206.0	1	1		68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	Ffg3_T2	00:00:09.500	31.536	163.424	2.47	1	0.00	25.99		4	208	1.5	4	208.0	1.5	1		69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	Ffg3_T2	00:00:10.000	30.3	163.403	2.69	1	0.00	25.99		4	209	11.5	4	209.0	11.5	1		70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	Ffg3_T2	00:00:10.500	28.955	163.369	2.37	1	0.00	25.99		4	212	1	4	212.0	1	1		71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	Ffg3_T2	00:00:11.000	27.768	163.394	2.42	1	0.00	25.99		4	213	1	4	213.0	1	1		72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Ffg3_T2	00:00:11.500	26.56	163.425	2.07	1	0.00	25.99		5	218	1	5	218.0	1	1		73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Ffg3_T2	00:00:12.000	25.526	163.445	2.04	1	0.00	25.99		7	221	1	7	221.0	1	1		75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Ffg3_T2	00:00:12.500	24.504	163.443	1.71	1	0.00	25.99		8	222	1	8	222.0	1	1		76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Ffg3_T2	00:00:13.000	23.65	163.435	1.62	1	0.00	25.99		10	222	1	10	222.0	1	1		77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	Ffg3_T2	00:00:13.500	22.84	163.414	1.32	1	0.00	25.99		11	221	1	11	221.0	6	2		78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	Ffg3_T2	00:00:14.000	22.185	163.474	1.43	1	0.00	25.99		11	221	5	11	220.0	1	1		81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	Ffg3_T2	00:00:14.500	21.52	163.732	1.28	1	0.00	25.99		11	220	1	11	219.0	1	1		82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	Ffg3_T2	00:00:15.000	21.02	170.194	1.62	1	0.00	25.99		11	219	1	13	217.0	1	1		83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
32	Ffg3_T2	00:00:15.500	20.557	170.786	1.87	1	0.00	25.99		13	217	1	27	216.0	15	1		85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	Ffg3_T2	00:00:16.000	20.217	171.697	2.21	1	0.00	25.99		27	216	15	39	216.0	1	1		86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	Ffg3_T2	00:00:16.500	19.907	172.73	2.13	1	0.00	25.99		39	215	1	52	203.0	1	1		88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

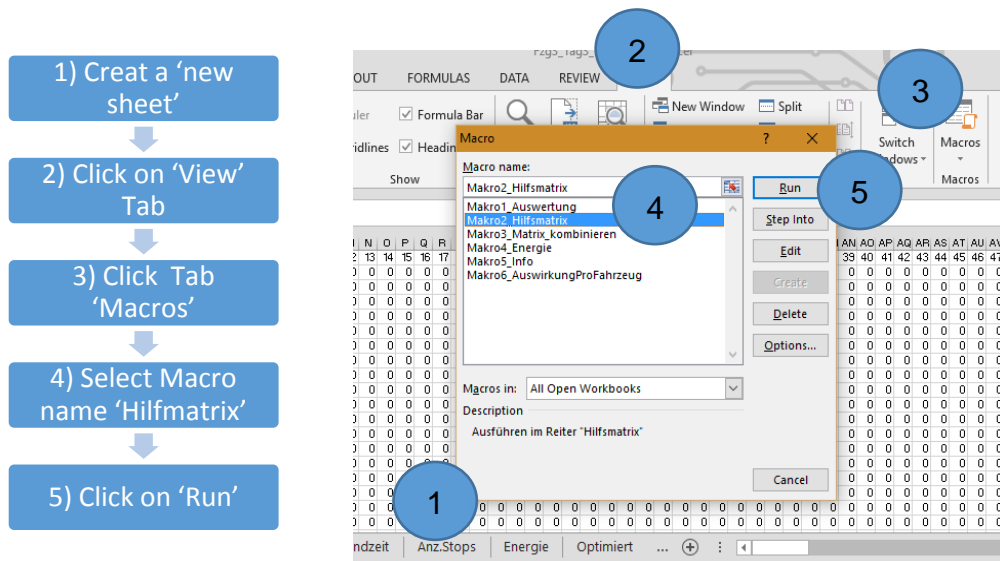
Furthermore, OCLSM presents break timing and number of halts at particular 'X' and 'Y' coordinates in matrix form. In the central part OCLSM lists the process total time considered as well as the total break time and total travel distances of the vehicle.

## Macro 2 – Hilfsmatrix/auxiliary matrix

Macro 2 generates the auxiliary matrix. With the help of this matrix continuity of coordinates within the coordinate system is generated. The auxiliary matrix is an essential component in order to accurately execute the subsequent macros.

Steps to calculate the 'auxiliary matrix'

1. Create new sheet named as 'Hilfsmatrix'.
2. Click on 'View' tab.
3. Click on 'Macros'.
4. Select Macro name 'Hilfsmatrix'.
5. Click on 'Run'



Within the resulting auxiliary matrix, the first row represents 'X' co-ordinates and the first vertical column represents 'Y' co-ordinates in serial arrangement as the general Cartesian coordinate system. All subsequent values represent the spatial arrangement of the investigated facility being represented by the neutral value '0'.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1		-19	-18	-17	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



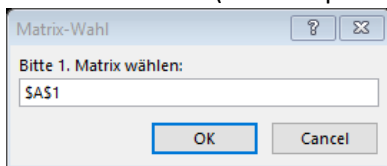
## Macro 3 - Matrix kombinieren/combination of matrices

Macro 3 combines two or more matrices and is used to generate two results namely 'break time duration' and 'number of stops' and involves simple matrix multiplication.

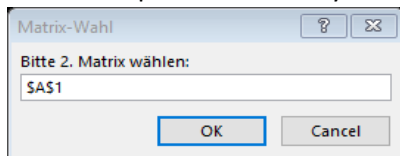
- **A) Break time duration:** Total break times throughout the whole working period are calculated. To get this matrix the matrices 'break time from data sheet' and 'auxiliary matrix' are combined.

Steps to calculate 'total break time duration'

1. Create new sheet named as 'Standzeit/total break time duration'
2. Click on 'View' tab
3. Click on 'Macros'
4. Select Macro name 'Matrix kombinieren'
5. Select 1<sup>st</sup> matrix (vehicle specific break time) from data sheet



6. Select complete 2<sup>nd</sup> auxiliary matrix.

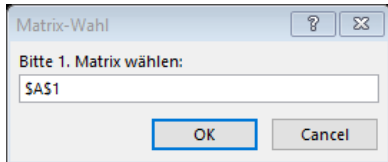


7. Click on combine the matrix.
8. Click on 'Run'.

- **B) Number of stops:** This evaluates total halts during the whole working period. To calculate this matrix the matrices namely 'number of stops from data sheet' and 'auxiliary matrix' are combined.

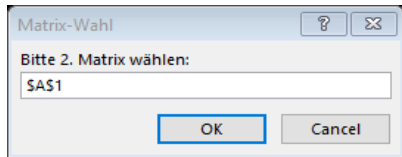
Steps to evaluate 'number of stops'

1. Create new sheet named as 'Anz. Stops'
2. Click on 'View' tab
3. Click on 'Macros'
4. Select Macro name 'Matrix kombinieren'
5. Select 2<sup>nd</sup> matrix (vehicle specific number of stops) from data sheet.



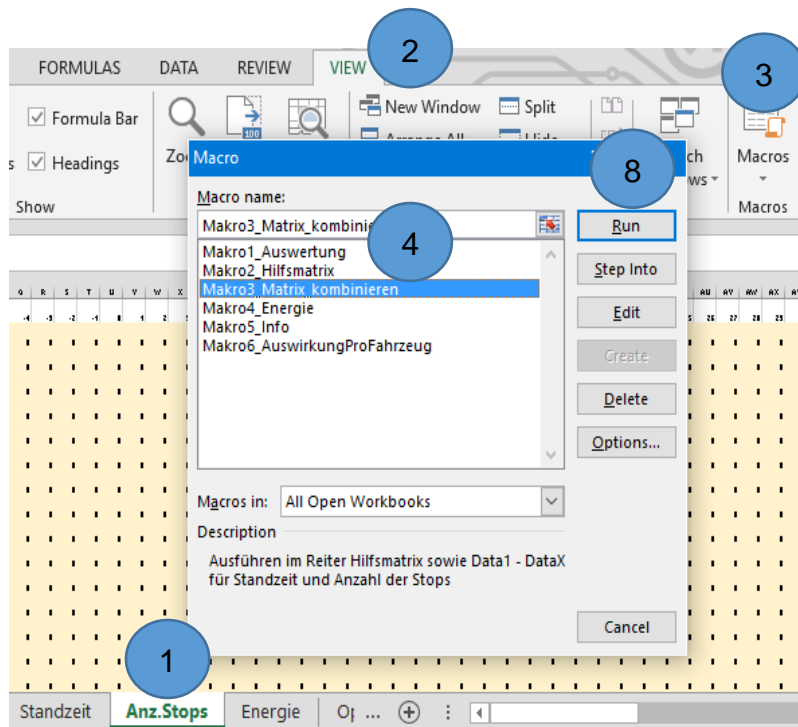
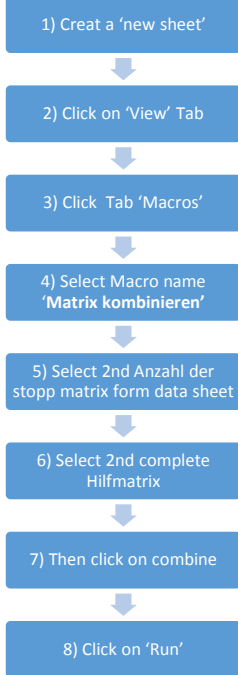
5

6. Select complete 2<sup>nd</sup> auxiliary matrix.



6

7. Click on combine the matrix.
8. Click on 'Run'.

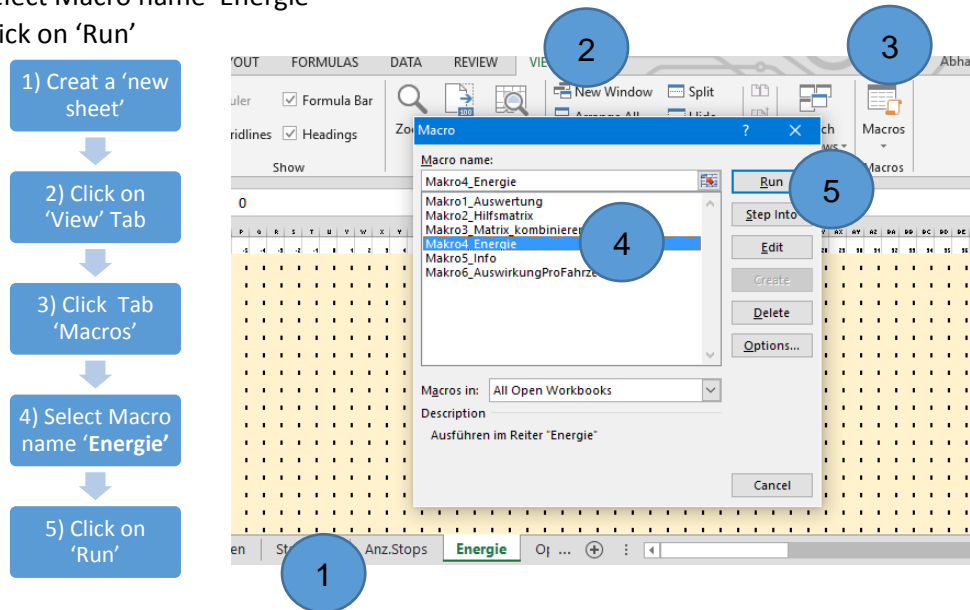


## Macro 4 – Energie/energy

Macro 4 is used to calculate the amount of rechargeable energy being available for vehicle battery charging during its operations in reference to its location. This energy values are multiplied with the values from tab 'Standzeit' and transmission capacity from tab 'Input'.

Steps to calculate the energy

1. Create new sheet named as 'Energie'
2. Click on 'View' tab
3. Click on 'Macros'
4. Select Macro name 'Energie'
5. Click on 'Run'



The macro 'Energie/energy' generates the allocation of recharge energy in reference to its location. In a second step, the macro operates idle time relocation in reference to a function based definition of the fundamental OCSLM covering distance.

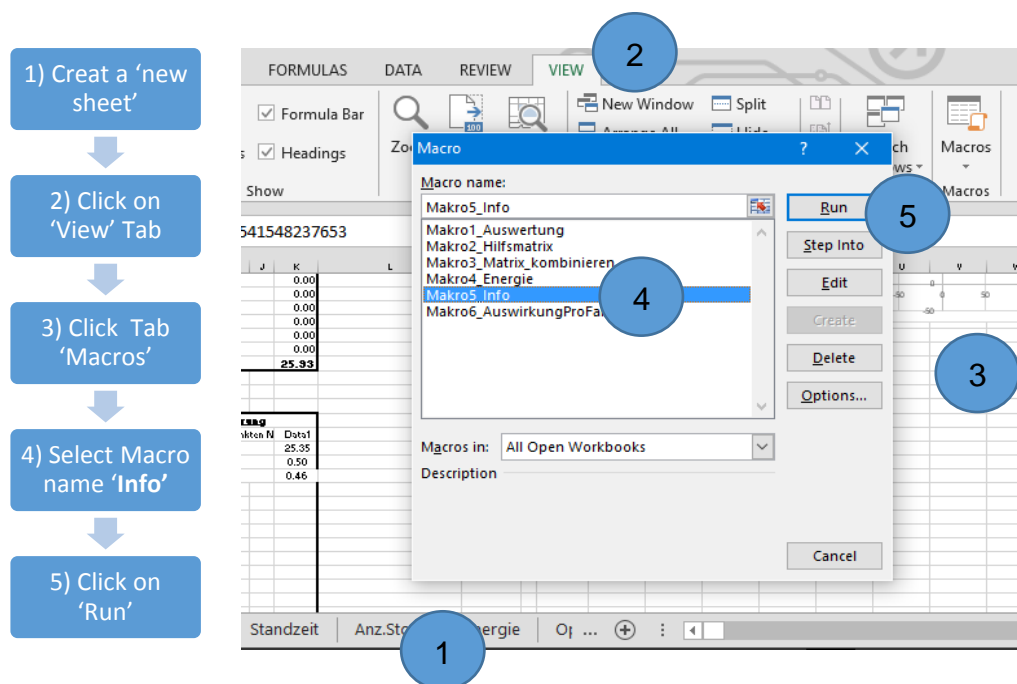
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1		-92	-91	-90	-89	-88	-87	-86	-85	-84	-83	-82	-81	-80	-79	-78
2	-93	493	657	1922	2035	7143	3381	16587	6685	22747	8520	17083	32549	7313	9022	4615
3	-92	9428	9361	10587	10590	15609	11600	24637	14356	29800	15601	26950	31011	14847	16820	12585
4	-91	2505	2344	3531	3535	8693	4752	17978	7818	24228	8769	20041	33673	8752	8369	6327
5	-90	8169	8154	9380	9383	14517	10361	23496	13189	28295	12583	25895	36535	10392	15846	11672
6	-89	326	197	1301	1172	6249	1903	14965	4554	21023	4582	16748	30065	4621	6840	2781
7	-88	272	199	1354	1261	6341	2048	15174	4689	21395	4795	16784	29811	4610	6844	2799
8	-87	194	140	1306	1197	6388	1961	15136	4679	21852	5033	16774	29553	4592	6840	2810
9	-86	17029	17185	18569	18647	24067	19797	26669	21942	40492	23314	34765	43469	22314	19858	17450
10	-85	8677	8690	9931	9841	15129	10658	15218	13325	31777	14207	25451	37580	13132	15366	11350

## Macro 5 – Info

Macro 5 Info analyses all input data and generates the summary of the simulated vehicle operations period in a tabular form.

Steps to run macro-5- Info

1. Create new sheet named as 'Info'.
2. Click on 'View' tab.
3. Click on 'Macros'.
4. Select Macro name 'Info'.
5. Click on 'Run'.



The parameters being generated by this OCSLM step are shown in the below table:

Dimension	Side condition	Value	Unit
covered distance		6.32	km
theoretical potential		28.69	kWh
recharge energy	$S = 10\text{m}$	8.08	kWh
	$E_{ij} > 0$	17.58	kWh
additional energy		9.51	kWh
fraction of th. potential	$S = 10\text{m}$	28.2	%
	$E_{ij} > 0$	61.3	%
top 3 potential	$E_{ij} > 0$	21.14	kWh
additional energy consumption ( $e_D$ )		0.60	kWh
non-usable potential		296	kWh

Furthermore, the worksheet info includes information on the top 3 charging station allocations that illustrate the theoretical potential that could be realised in the three locations of highest energy input as expression of the Maximum Covering Location Model. This value includes losses and waste, such as 'additional energy consumption' and 'non-usable potentials'

due to additional handling actions and time losses that occur in reference to the usage of occasional charging.

Furthermore, the exact allocation of charging stations is given in x- and y-coordinates according to the below table. The fraction of recharge energy in reference to the generated charging station allocations is given by ' $E_{\text{recharge}}$ ', whereas the splitting in the last columns considers the recharge energy in reference to the investigated vehicles as expressed by 'Data1' and 'Data2'.

Top 3 charging stations $S_{in}$						Top 3 charging stations $E_{ij}$					
no.	x-axis	y-axis	$E_{\text{recharge}}$	Data 1	Data 2	no.	x-axis	y-axis	$E_{\text{recharge}}$	Data 1	Data 2
1	-1.06	23.85	3.99 kWh	3.99	0.00	1	-0.37	35.12	11.65 kWh	9.73	1.92
2	51.69	95.63	2.37 kWh	1.03	1.34	2	52.00	85.84	6.52 kWh	2.53	3.99
3	79.00	116.00	1.72 kWh	1.72	0.00	3	62.36	116.82	2.96 kWh	1.77	1.19
<b>sum</b>			<b>8.08 kWh</b>	6.74	1.34	<b>sum</b>			<b>21.14 kWh</b>	14.03	7.10

## Macro 6 - Auswirkungen pro Fahrzeug/impact analysis

The execution of the impact analysis reduces the impact from the charging station allocation for occasional recharging to the energy balance of individual vehicles being investigated. By this the potentials for individual system adaptations/optimisations are highlighted and evaluated towards its contribution to increased efficiency (cost aspect) and sustainability.

1) Create a 'new sheet'

2) Click on 'View' Tab

3) Click Tab 'Macros'

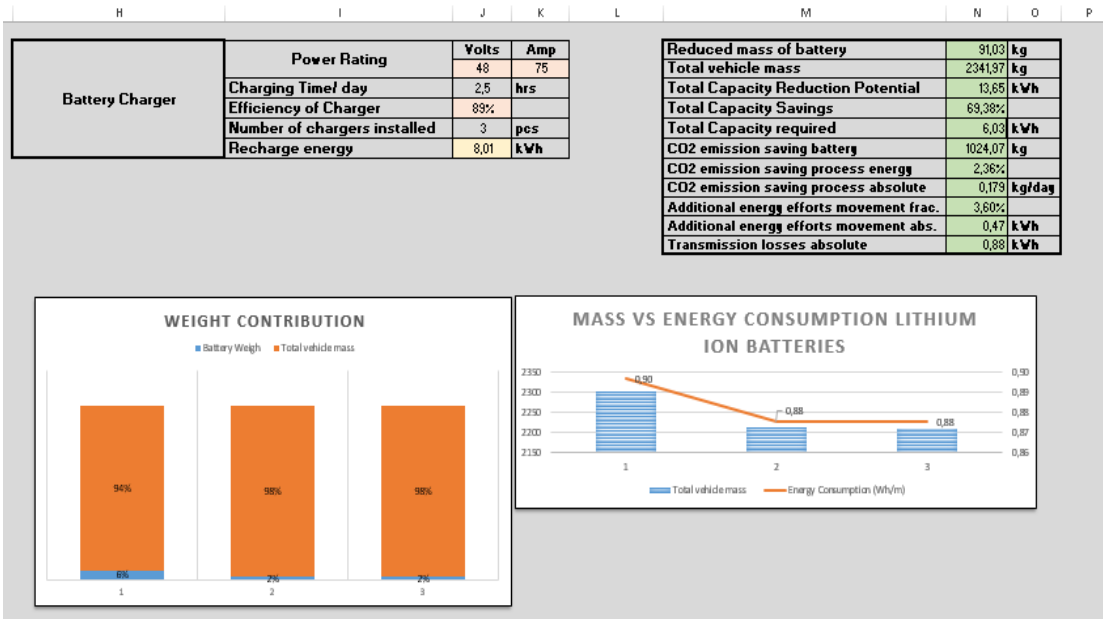
4) Select Macro name 'Auswirkungen pro Fahrzeug'

5) Click on 'Run'

Simulation results are subsequently fed into the impact analysis worksheet.

		V	Ah	kWh			Volts	Amp
Linde E14	Battery Capacity	48	440	21,12	Battery Charger	Power Rating	48	75
	Battery Weight	140,8	kg			Charging Time/day	2,5	hrs
	Drive Distance	12000	m			Efficiency of Charger	90%	
	Vehicle Speed	1,38	m/sec			Number of chargers installed	3	pcs
	Total vehicle mass	2301,8	kg			Recharge energy	8,19	kWh
	Lifted Mass	1400	kg					
	Additional driving distance	270	m					
Battery	Energy Density (Li)	0,15	kWh/kg					
	Depth of Discharge	0,85						

The results of the vehicle individual investigations are displayed within the output worksheet.



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**Appendix E - Declaration of agreement**

# Declaration of agreement

## **Experimental investigations on process routing and sequencing in the field of assembly line material supply.**

**Supervised by:**

Patrick Fekete (M.Eng)  
Scientific Officer  
School of Engineering and Architecture  
SRH Hochschule Heidelberg

**Description:**

The process analysis targets to identify, record and analyse relevant parameters in the field of assembly line material supply. Relevant data is defined as vehicle routing, covered process distances and times, consumed energy as well as process related break and idle times of individual vehicles.

**Risks and Advantages:**

The participation in the pursued investigations is not linked to any additional risks or direct advantages.

**Cost and Payments:**

As data collection, i.e. recording, is operated within regular production, there is no additional cost for the participating parties so that also no financial compensation is paid.

**Confidentiality:**

All recorded information is process related information that is anonymised. Person related analysis or performance specific evaluation are not possible and target of the research. The generated information are only available to participating academic researchers. Results can be offered to other researchers, but no information which would lead to participant identification.

**To stop investigations:**

Participants are not obliged to participate in the investigations and can stop participating at any time. The decision about stopping to participate has no further impact to the participants and does not result in any dis-/advantage.

**Voluntary consent:**

The above stated information were explained to me in detail and referring questions were answered. I know that future questions will also be answered by the operating staff. By my signature I confirm that I want to participate in the described investigations.



---

**Acceptance participant**

---

Name, Prenom participant

---

Position / Affiliation

---

Date, Signature

---

**Confirmation investigation authority**

I confirm that the target and the execution of the pursued investigations as well as accompanying potential advantages and risks were thoroughly explained to the participants. Related questions have been answered.

---

Name, Surname authority

---

Position / Affiliation

---

Date, Signature authority

## Appendix F - Individual case vehicle results

### Vehicle 5

Due to its trawler function with focus on the supply of the assembly lines 4 and 5, the movement profile (Figure 0-1) of vehicle 5 is centred alongside the line implementation. The idle time profile shows a similar break time distribution which is concentrated in the area from (58/95) to (58/130).

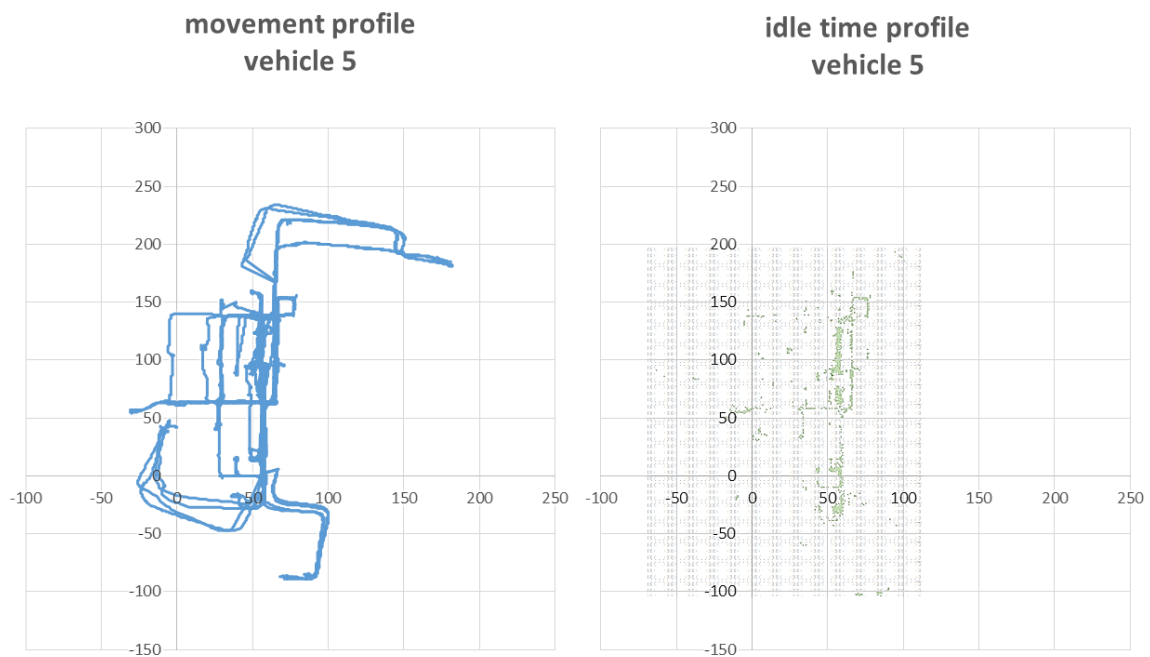


Figure 0-1: Movement (left) and idle time profile (right) vehicle 5

The average gross process drive distance as displayed in Table 0-1 is 16,142.43m, whereas the maximum drive distance was recorded within the data set on day 33 with 18,609.32m. Average velocity of the processes operated by vehicle 5 is determined as 1.85m/s.

Day	Total duration	Process Drive Distance	Average Velocity	Charging potential
	[h]	[m]	[m/s]	[kWh]
⋮				
33	8.00	18,609.32	1.93	21.36
36	8.00	10,720.52	1.69	21.93
42	8.00	11,971.14	1.63	21.69
46	8.00	18,402.57	1.79	18.36
⋮				
average	8.00	16,142.43	1.85	20.80

Table 0-1: Process data vehicle 5

**Location-allocation – vehicle 5**

The charging station distribution in reference to the day based differentiation shows no explicit patterns. This can be referred to the vehicle’s trawler function that implies a wider geographic coverage of the production facility.

The S<sub>10</sub> charging station placement shows a more widespread distribution (see Figure 0-2 -right), whereas OCSLM centralises the most beneficial charging station allocations, so that OCSLM charging station allocations show an overlap in the covering distances and the covered idle time locations.

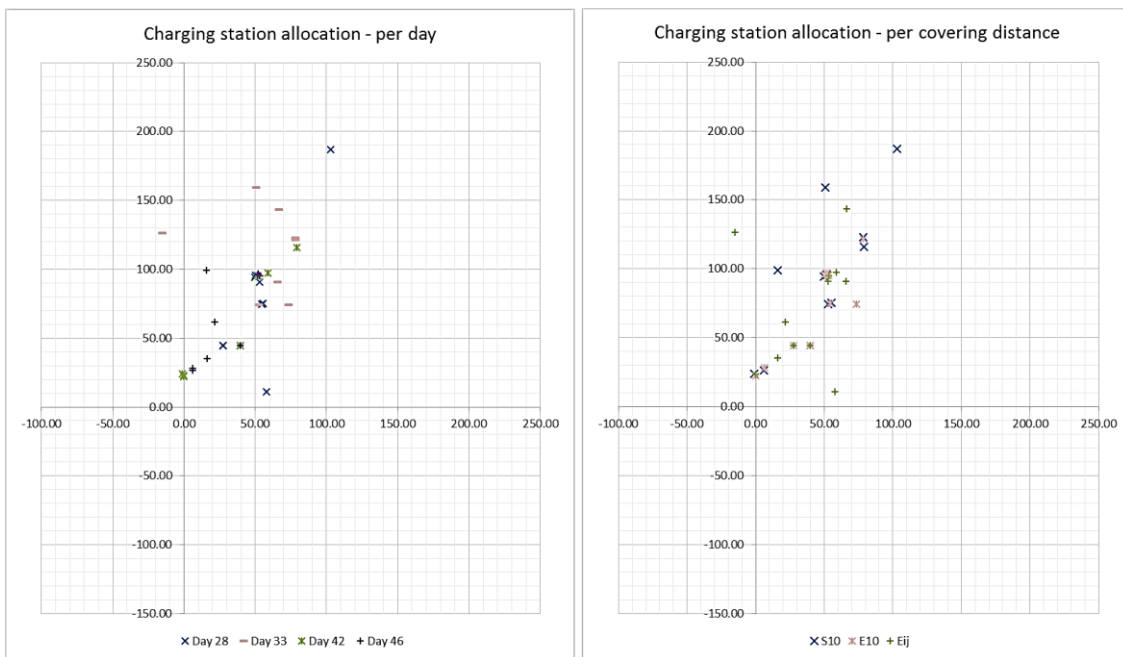


Figure 0-2: Charging station allocation vehicle 5 - per day (left); per covering distance (right)

### Simulation results – vehicle 5

The consideration of the total of 30 days recorded shows the minimal recharge energy of  $S_{10}$  to be realised on day 42 with a total of 4.10kWh (see also Table 0-2). The OCSLM charging station allocation results in an increased recharge energy for  $E_{ij10}$  of 10.38kWh, i.e. +42.39%, and for  $E_{ij}$  for an additional 3.12kWh to a total of 13.50kWh. The average increase from  $S_{10}$  to  $E_{ij}$  is numbered as +55.69%.

The additional drive distance increases from  $E_{ij10}$  to  $E_{ij}$  for 41.89% in average, from average 205m to 353m.

Day	Charging potential	Static charging potential $S_{10}$	Practical charging potential $E_{ij10}$	Additional drive distance $E_{ij10}$	Practical charging potential $E_{ij}$	Additional drive distance $E_{ij}$
	[kWh]	[kWh]	[kWh]	[m]	[kWh]	[m]
⋮						
33	21.36	6.09	10.59	282.68	14.75	494.09
36	21.93	7.49	12.63	76.75	13.96	119.39
42	21.69	4.10	8.52	151.87	12.46	258.18
46	18.36	4.17	8.37	305.34	12.55	580.14
⋮						
average	20.80	5.98	10.38	205.52	13.50	353.65

Table 0-2: Simulation results vehicle 5

The difference from ‘max.’ and ‘min.’ values of recharge energy in comparison to the average value decreases in the case study on vehicle 5, whereas the ratio of deviation from the average doesn’t change (see Figure 0-3). Evaluating the decreasing benefit of  $E_{ij}$ , i.e. the increased recharge energy being available, an increasing additional drive distance for the maximal potential can be observed, whereas for the minimal consideration, the additional drive distance decreases. These two trends jointly contribute in order to decrease the benefit of the maximum and average case over the minimum case, so that the difference of additional recharge energy at  $E_{ij10}$  from max. to min. of 4.26kWh decreases at  $E_{ij}$  to 2.29kWh. Its meaning to the overall energy balance, i.e. the potential for system downsizing and resource saving are evaluated in the subsequent impact analysis on vehicle 5.

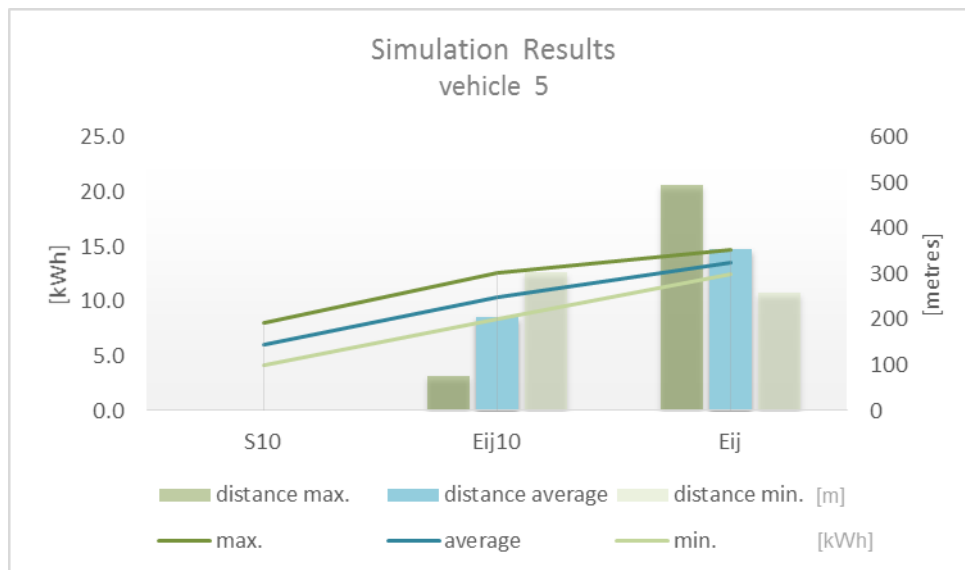


Figure 0-3: Simulation results vehicle 5

### Impact analysis – vehicle 5

The evaluation of system integration for occasional recharging shows, that the maximal battery downsizing can be achieved in reference to  $S_{10}$  at the sample day 36. As displayed in Table 0-3, this potential cannot be observed for all recorded days of vehicle 5, so that in average the downsizing potential is approximately 10.57kWh, so that the required battery capacity is determined to be 9.11kWh. Major impact to the system adaption emerges from day 46, which allows the battery capacity reduction for 7.47kWh to a minimum of 12.21kWh only.

The charging station implementation approach  $E_{ij10}$  increases the minimal additional recharge energy to 8.37kWh of day 46, so that the provided battery capacity can be downsized to 6.81kWh, which is 55.77% of the required capacity in reference to the  $S_{10}$  approach. The maximal battery downsizing potential is achievable in reference to the  $E_{ij}$  definition only. The required recharge energy for maximal battery downsizing was only reached by this charging station allocation definition. By this, the impact from decreased drive distance and by this decreased additional energy consumption of charging station approaching of the minimal case does not change the results on the downsizing potential as both max. and min. cases are sufficient for maximal battery downsizing.

Day	Battery capacity reduction	Required capacity	CO2 Reduction battery	Reduction process energy	CO2 reduction process	Additional energy efforts movement	Additional energy efforts movement	Transmission losses
$S_{10}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
...								
33	10.00	9.68	749.89	2.68	0.222	x	x	0.67
36	15.74	3.94	1,180.80	2.68	0.128	x	x	0.82
42	13.67	6.01	1,024.99	2.68	0.143	x	x	0.45
46	7.47	12.21	560.09	0	0	x	x	0.46
...								
average	10.57	9.11	792.54	2.01	0.072			0.46

$E_{ij10}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
...								
33	15.29	4.39	1,146.94	2.68	0.222	1.52	0.22	1.16
36	15.74	3.94	1,180.80	2.68	0.128	0.72	0.06	1.39
42	15.74	3.94	1,180.80	2.68	0.143	1.27	0.12	0.94
46	12.87	6.81	965.10	2.68	0.220	1.66	0.23	0.92
...								
average	14.31	5.38	1,072.95	2.68	0.182	1.47	0.18	0.93

$E_{ij}$	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
...								
33	15.74	3.94	1,180.80	2.68	0.380	2.66	0.38	1.62
36	15.74	3.94	1,180.80	2.68	0.128	1.11	0.09	1.54
42	15.74	3.94	1,180.80	2.68	0.143	2.16	0.2	1.37
46	15.74	3.94	1,180.80	2.68	0.220	3.15	0.45	1.38
...								
average	15.74	3.94	1,180.80	2.68	0.182	2.66	0.33	1.38

Table 0-3: Impact analysis results vehicle 5

In contrast to the values on battery capacity reduction, maximal reduction of process energy is achieved by the battery mass reductions of both,  $E_{ij10}$  and  $E_{ij}$  which is proved by the average values according to Table 0-3 and displayed in Figure 0-3. The battery mass reduction based on the charging station allocation of  $S_{10}$  is not sufficient in order to achieve the maximum energy reduction of 2.68%.

The achievement of maximal battery downsizing results in increased energy efforts for charging station approaching, which is at 1.47% for  $E_{ij10}$  respectively 2.66% for  $E_{ij}$ , whereas this increase is numbered by an additional energy consumption of 0.6kWh.

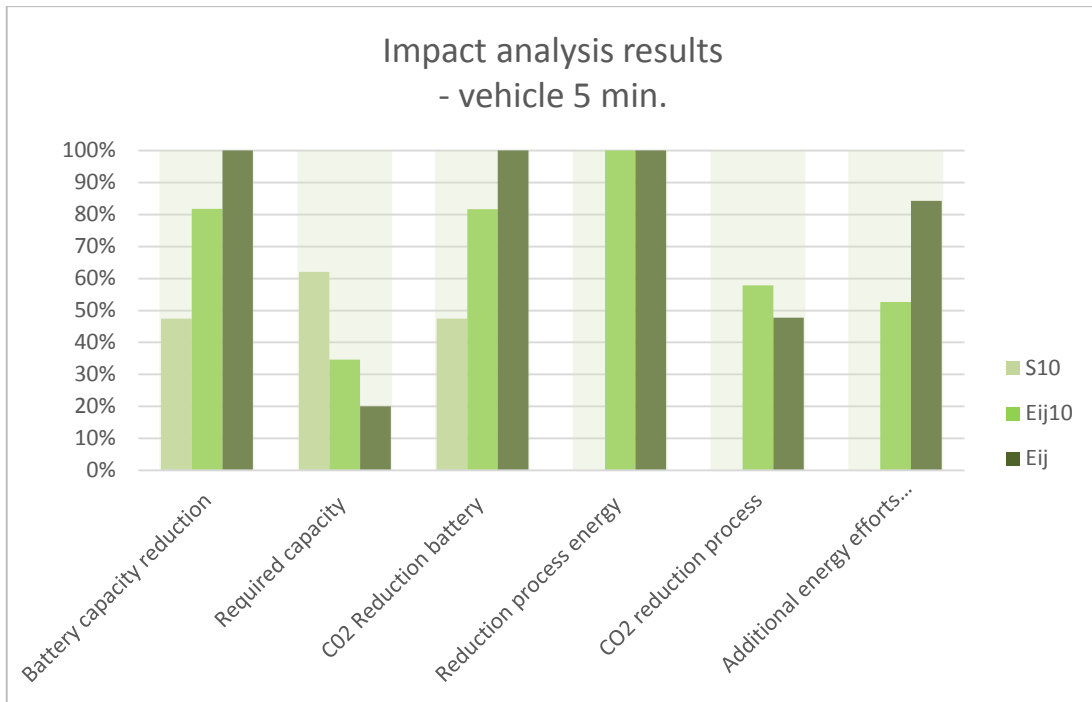


Figure 0-4: Impact analysis results minimum recharging vehicle 5

### Vehicle 6

Vehicle 6 transports average weights of 900kg by supplying engines and gear drives to the production lines 4 and 5. Drive routes are similar to the ones of vehicle 5, so that the idle time profile shows an increased appearance of break times alongside these lines with a bigger number of short term process interruptions of two to five seconds.

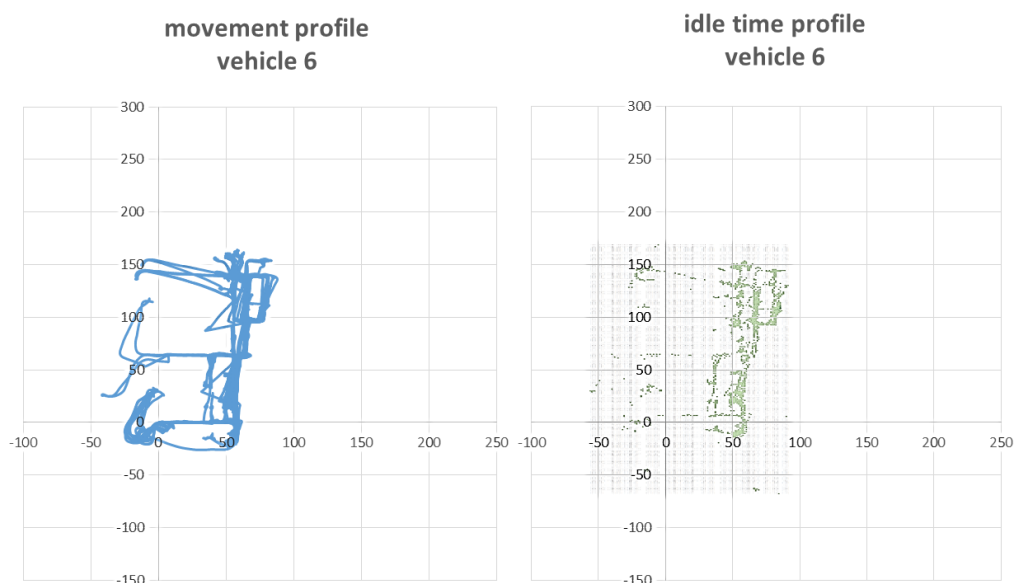


Figure 0-5: Movement (left) and idle time profile (right) vehicle 6

Gross process drive distances range from 9,448.08m up to 17,731.39m with an average distance of 14,997.67m. Average velocity corresponds to the previously displayed vehicles, so that it ranges around 1.84m/s (see Table 0-4).

Day	Total duration	Process Drive Distance	Average Velocity	Charging potential
	[h]	[m]	[m/s]	[kWh]
⋮				
20	8.00	16,550.78	1.62	22.44
25	8.00	9,448.08	1.97	20.42
27	8.00	11,425.13	2.02	20.99
30	8.00	17,731.39	1.54	17.16
⋮				
average	8.00	14,997.67	1.84	20.01

Table 0-4: Process data vehicle 6

### Location-allocation – vehicle 6

The day based distribution (see Figure 0-6) of the most beneficial charging spots for the chosen samples shows an accumulation of individual spots for different days in the area (50/100) to (75/130). A second accumulation of charging spots is allocated in the area between (30/10) and (50/30) which contains a charging spot recommendation for all displayed days. The process data on day 27 further suggests a charging spot around (25/220), whereas no other day's idle time profile allocates a charging station in this area.

Referring to the right part of Figure 0-6 shows that the exogenous covering distance proposes a corresponding charging station allocation in (25/223) based on the influence of recharge energy of 0.56kWh. The changed allocation definition of  $E_{ij10}$  and  $E_{ij}$  relocates this charging spot to a more beneficial charging spot in order to increase the recharge energy over all considered days. Considering the basic assumption of a minimum of two to three charging spots being approachable per vehicle and considered day, for  $E_{ij10}$  a minimum of 1.23kWh in (55/159) can be recharged in the suggested locations instead of 0.56kWh.



In the final potential evaluation the accumulation of charging spots in the area (50/100) to (75/130) is evaluated towards the positive impact to the vehicle energy balance in order to determine the most beneficial spots out of the recommended allocations.

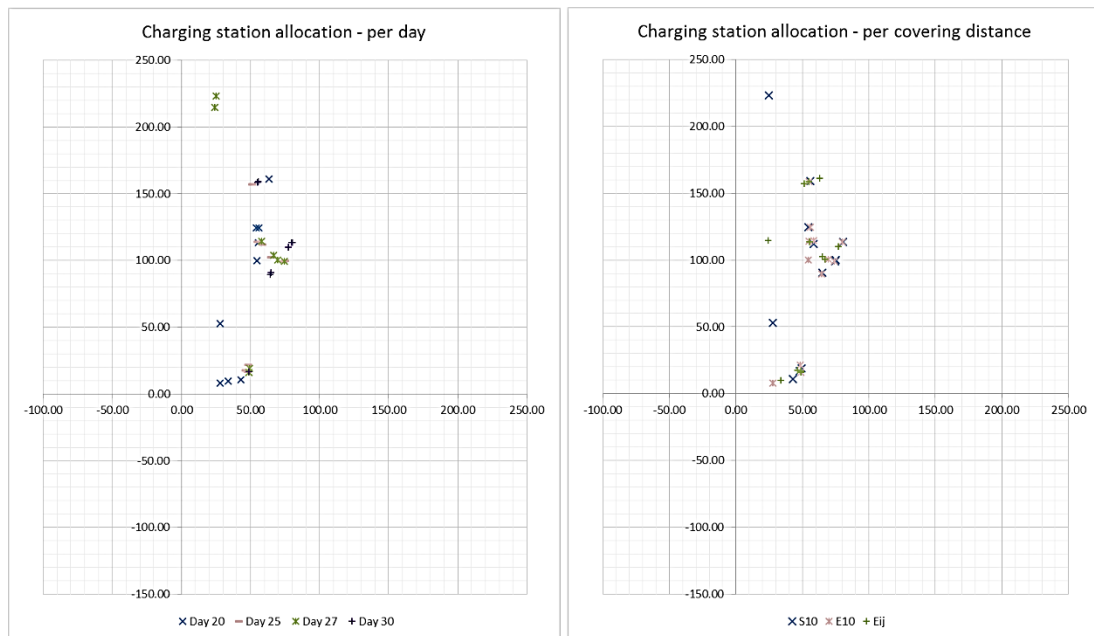


Figure 0-6: Charging station allocation vehicle 6 - per day (left); per covering distance (right)

### Simulation results – vehicle 6

The review of the total of 21 recorded days for vehicle 6 shows the minimal recharge energy for  $S_{10}$  to be 4.59kWh and 6.09kWh for  $E_{ij10}$  within day 27, whereas the limiting day for the allocation determination of  $E_{ij}$  is presented by day 30 with a total of 9.14kWh. For the minimum consideration, recharge energy increases  $S_{10}$  to  $E_{ij}$  for 50.22%. The additional drive distances for day 20 and 30 show high additional efforts of +6.95% respectively +5.10% of additional energy consumption. The average value of additional drive distance for vehicle 6 is 52.56%, respectively 39.75% lower (see also Table 0-5).

Day	Charging potential	Static charging potential $S_{10}$	Practical charging potential $E_{ij10}$	Additional drive distance $F_{ij10}$	Practical charging potential $E_{ij}$	Additional drive distance $F_{ij}$
	[kWh]	[kWh]	[kWh]	[m]	[kWh]	[m]
⋮						
<b>20</b>	22.44	7.38	11.18	405.84	15.77	1,149.88
<b>25</b>	20.42	4.89	10.73	170.23	13.33	278.56
<b>27</b>	20.99	4.59	6.09	130.89	9.38	196.33
<b>30</b>	17.16	4.94	8.07	452.57	9.14	905.16
⋮						
<b>average</b>	20.01	5.04	8.89	255.55	11.51	545.39

Table 0-5: Simulation results vehicle 6

The illustration of the maximum, average and minimum values of vehicle 6 according to Figure 0-7 shows diverging values. While the absolute maximum value of recharge energy grows, average and minimum values converge, as a result of the deviation from minimum to maximum values.

Increasing additional energy consumption from  $E_{ij10}$  to  $E_{ij}$  lower the benefit from additional energy input due to the cost of additional efforts, so that increased energy input does not necessarily contribute to the achievement of the maximal downsizing potential (see Table 0-6). The influence to the energy balance is considered in the impact analysis.

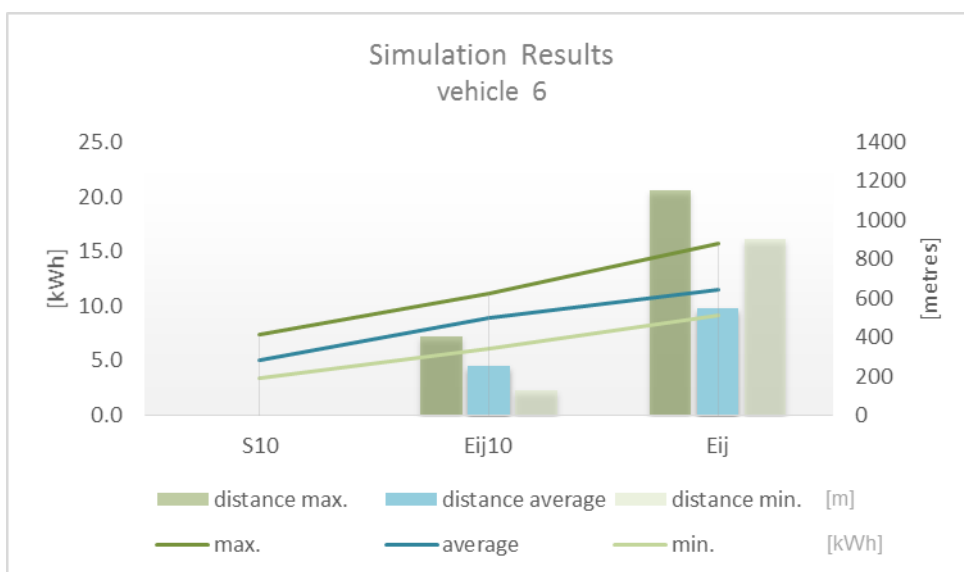


Figure 0-7: Simulation results vehicle 6

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### Impact analysis – vehicle 6

The review of values on the integration for occasional recharging shows the maximal battery downsizing in reference to  $S_{10}$  at the sample day 25. As displayed in Table 0-6, the maximum potential is not observed at the majority of the recorded days of vehicle 6, so that in average the downsizing potential is determined at 10.13kWh, so that the average battery capacity required is determined to be 9.56kWh. Limiting impact to the system adaption is set by day 27, which allows the battery capacity reduction for 6.18kWh to a minimum of 13.50kWh.

The charging station allocation of  $E_{ij10}$  increases the minimal additional recharge energy to 7.94kWh within day 27, so that the provided battery capacity can be downsized to 11.74kWh. The maximal battery downsizing potential is not achievable in this case study as shown by the average value of  $E_{ij}$  (see Table 0-6). The average required recharge energy for maximal battery downsizing is determined to be 10.67kWh which is not reached by the entire number of investigated cases of vehicle 6. The maximal downsizing potential of the limiting day 27 is about 11.81kWh to a minimal required battery capacity of 7.87kWh.

Day	Battery capacity reduction	Required capacity	CO <sub>2</sub> Reduction battery	Reduction process energy	CO <sub>2</sub> reduction process	Additional process	Additional energy efforts movement	Additional energy efforts movement	Transmission losses
S <sub>10</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]	
⋮									
20	12.14	7.54	910.60	2.48	0.198	x	x	0.81	
25	15.74	3.94	1,180.80	4.96	0.226	x	x	0.54	
27	6.18	13.5	463.42	2.48	0.231	x	x	0.5	
30	8.11	11.57	608.53	2.48	0.212	x	x	0.54	
⋮									
average	10.13	9.56	759.57	3.10	0.205			0.68	

E <sub>ij10</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
20	15.74	3.94	1,180.80	4.96	0.396	2.45	0.33	1.23
25	15.74	3.94	1,180.80	4.96	0.226	1.80	0.14	1.18
27	7.94	11.74	595.78	2.48	0.231	1.15	0.18	0.67
30	11.8	7.88	884.71	2.48	0.212	2.55	0.38	0.89
⋮								
average	13.77	5.91	1,032.76	3.72	0.304	2.50	0.36	1.06

E <sub>ij</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
20	15.74	3.94	1,180.80	4.96	0.396	6.95	0.93	1.73
25	15.74	3.94	1,180.80	4.96	0.226	2.95	0.23	1.47
27	11.81	7.87	886.07	2.48	0.231	1.72	0.28	1.03
30	13.05	6.63	979.12	2.48	0.212	5.10	0.75	1.01
⋮								
average	14.40	5.29	1,079.96	3.72	0.304	6.03	0.84	1.37

Table 0-6: Impact analysis results vehicle 6

In line with the values on battery capacity reduction, maximal reduction of process energy is not achieved within this case study as maximum downsizing is not realised. The battery mass reduction based on the charging station allocation of S<sub>10</sub>, E<sub>ij10</sub> and E<sub>ij</sub> is not sufficient in order to achieve the maximum energy reduction of 4.96%. The process energy consumption as well as the achieved CO<sub>2</sub> reductions of the handling processes for the minimum cases remain at the same level for all covering distance definitions as the difference in mass reduction and deviations of the associated process energy consumption is at low level.

The comparison of the additional energy efforts for additional movement of vehicle 6 (see Figure 0-8) and 5 (see Figure 0-3), which are affiliated to the same assembly lines, shows that a higher fraction of additional efforts does

not necessarily result in decreased values within the potential analysis for battery downsizing, so that the importance of case related investigations becomes apparent.

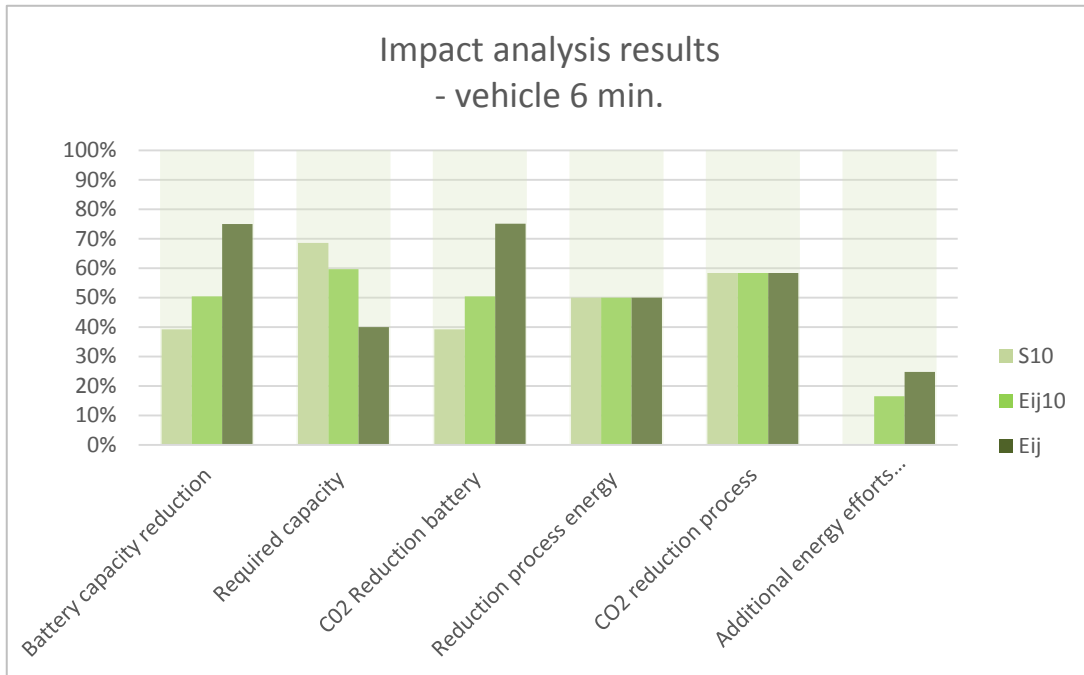


Figure 0-8: Impact analysis results minimum recharging vehicle 6

## Vehicle 7

Vehicle 7 is the second vehicle with trawler functions within the sample choice. Its supply function focuses on the provision of components to all investigated assembly lines with average weight of transported units of 1,100kg. The idle time profile as per Figure 0-9 shows several idle time spots distributed alongside the supporting assembly lines whereas the numbering and evaluation is part of the simulation analysis as subsequent part of the location-allocation modelling.

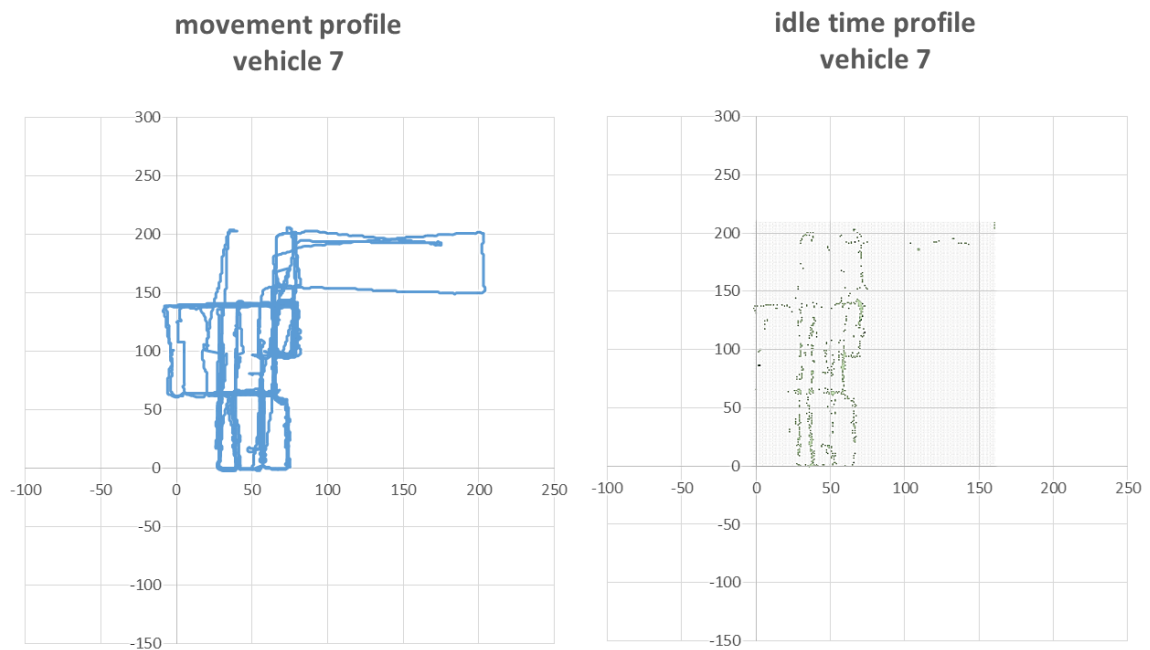


Figure 0-9: Movement (left) and idle time profile (right) vehicle 7

Process data according to Table 0-7 such as drives distances show a lower level compared to the remaining vehicles whereas average process speed is higher. Also the average charging potential shows higher values so that the process profile of this vehicle shows vehicle 7 operations on short process ways on high transfer speed which results in an increased number of idle times that are subject to further potential evaluation.

Day	Total duration	Process Drive Distance	Average Velocity	Charging potential
	[h]	[m]	[m/s]	[kWh]
⋮				
24	8.00	7,698.47	2.31	24.51
26	8.00	7,821.96	1.92	24.56
29	8.00	9,367.35	2.00	19.03
30	8.00	10,671.33	1.85	24.47
⋮				
average	8.00	8,573.47	2.00	23.38

Table 0-7: Process data vehicle 7

### Location-allocation – vehicle 7

The charging location illustrations as displayed in Figure 0-10 highlights the intense usage of the trawler vehicle on the overall main drive route in the corridor around (80/Y) including a deviation around the spot in (0/85).

The covering distance based examination of the most beneficial charging stations (see Figure 0-10 right part) shows the congruent allocation of a charging station around (74/206) that is preferred by all three covering distance definitions with an additional energy input of 1.43kWh. The differing allocation methods slightly relocate the charging station coordinates from  $S_{10}$  definition (73.52/200.24) to (74/206) for  $E_{ij10}$  and  $E_{ij}$ , whereas the optimisation leads to a minimal increase of recharge energy in the 3<sup>rd</sup> and 4<sup>th</sup> digit only, so that both allocations are evaluated to be of the same positive contribution to the energy balance.

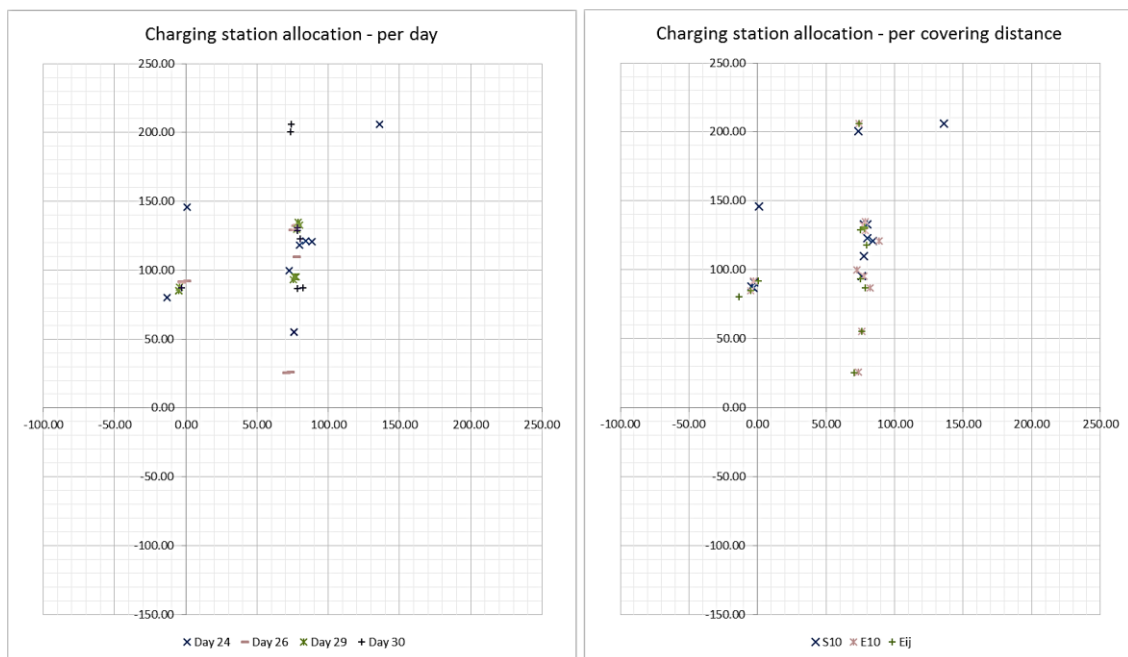


Figure 0-10: Charging station allocation vehicle 7 - per day (left); per covering distance (right)

### Simulation results – vehicle 7

Average recharge energy is determined at 5.31kWh for  $S_{10}$ ; 9.71kWh for  $E_{ij10}$  and 11.89kWh for  $E_{ij}$ . This represents an increase from  $S_{10}$  over  $E_{ij10}$  to  $E_{ij}$  of +45.31% respectively +18.37% and a total of +55.35%. Referring to the minimum values shows lower values according to Table 0-8 that result in the usage of around 17.31%, 26.52% and 31.14% of the theoretical charging potential.

Day	Charging potential	Static charging potential $S_{10}$	Practical charging potential $E_{ij10}$	Additional drive distance $E_{ij10}$	Practical charging potential $E_{ij}$	Additional drive distance $E_{ij}$
	[kWh]	[kWh]	[kWh]	[m]	[kWh]	[m]
⋮						
<b>24</b>	24.51	5.01	7.42	366.33	11.71	680.32
<b>26</b>	24.56	4.26	12.65	382.31	15.09	509.74
<b>29</b>	19.03	5.57	9.02	590.86	11.61	886.29
<b>30</b>	24.47	5.50	6.49	381.28	7.62	571.91
⋮						
<b>average</b>	23.38	5.31	9.71	440.81	11.89	635.97

Table 0-8: Simulation results vehicle 7

The additional drive distance for the max. consideration shows similar values for  $E_{ij10}$  and  $E_{ij}$  which goes in line with the equal distribution of charging stations according to Figure 0-10 - right. The equal distribution highlights the joint basis of an endogenous covering distance whereas  $E_{ij10}$  additionally bears an exogenous limitation, so that slight differences are still existent.

As displayed in Figure 0-11 and also observed within the other executed cases studies, the ratio of difference from 'min.' to 'average' and 'max.' values among the alternative covering distance definitions is continuous, so that a continuous growth can be observed.

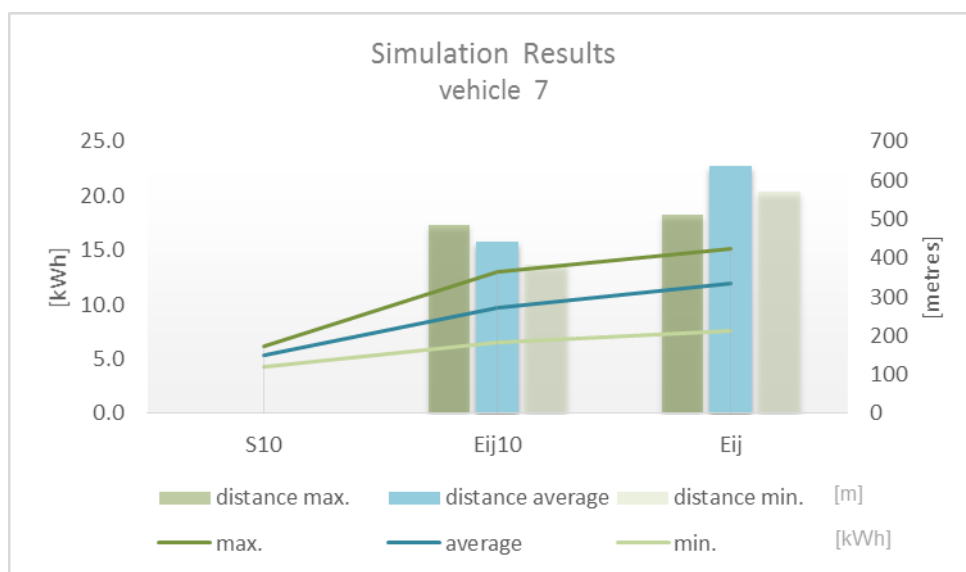


Figure 0-11: Simulation results vehicle 7



### Impact analysis – vehicle 7

The impact analysis on the integration for occasional recharging shows the maximal battery downsizing for the S<sub>10</sub> consideration at the sample day 26. The maximum potential for system downsizing cannot be observed for the remaining days of vehicle 7, so that the average downsizing potential is determined at 12.56kWh and the average battery capacity being required for constant process operations is determined to be 7.13kWh. The minimum investigation with impact to system design is based on day 29, which enables battery capacity reduction for 9.95kWh to a minimum of 9.73kWh.

Day 30 was determined by the simulation analysis as the day of minimal recharge energy being realised (see Table 0-8), whereas due to the process structures, driving patterns and the inherent process energy consumption, day 29 with a recharge energy of 9.02kWh limits the maximal downsizing potential to minimum of 5.67kWh, while day 30 enables the realisation of the full downsizing potential (see Table 0-9).

Day	Battery capacity reduction	Required capacity	CO2 Reduction battery	Reduction process energy	CO2 reduction process	Additional energy efforts movement	Additional energy efforts movement	Transmission losses
S <sub>10</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
...								
24	12.19	7.49	914.26	2.36	0.155	x	x	0.55
26	15.74	3.94	1180.80	4.73	0.187	x	x	0.47
29	9.95	9.73	746.07	2.36	0.189	x	x	0.61
30	15.16	4.52	1136.97	4.73	0.128	x	x	0.61
...								
average	12.56	7.13	941.52	3.55	0.159	0	0	0.61

E <sub>ij10</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
...								
24	15.03	4.65	1,126.91	4.73	0.155	4.76	0.53	0.82
26	15.74	3.94	1,180.80	4.73	0.187	4.89	0.33	1.39
29	14.01	5.67	1,050.48	2.36	0.189	6.31	0.87	0.99
30	15.74	3.94	1,180.80	4.73	0.255	3.57	0.33	0.71
...								
average	14.88	4.81	1,115.64	4.26	0.222	4.94	0.60	0.85

E <sub>ij</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
...								
24	15.74	3.94	1,180.80	4.73	0.311	8.84	0.98	1.29
26	15.74	3.94	1,180.80	4.73	0.187	6.52	0.44	1.66
29	15.74	3.94	1,180.80	4.73	0.378	9.46	1.28	1.28
30	15.74	3.94	1,180.80	4.73	0.255	5.36	0.49	0.84
...								
average	15.74	3.94	1,180.80	4.73	0.317	7.41	0.89	1.06

Table 0-9: Impact analysis results vehicle 7

The average downsizing potential of  $E_{ij10}$  is about 14.88kWh, i.e. 94.53% of the total battery mass reduction potential, while charging station allocation on the OCSLM basis of  $E_{ij}$  reaches the full downsizing potential as per Figure 0-12. The discrepancy of the minimum case to full downsizing shows a lower reduction of battery production related CO<sub>2</sub> emission of approximately 11%.

Referring to the minimum values, process energy and process related CO<sub>2</sub> emissions are reduced by 50% only of the maximal potential for  $S_{10}$  and  $E_{ij10}$ . This can be explained by the fraction of additional energy efforts for  $E_{ij10}$  with around 68% and  $E_{ij}$  with around 78% of the maximal additional efforts of 9.46% of the total process energy. The total of additional drive distance in reference to the short process distances as described in Table 0-8 explain this impact relation.

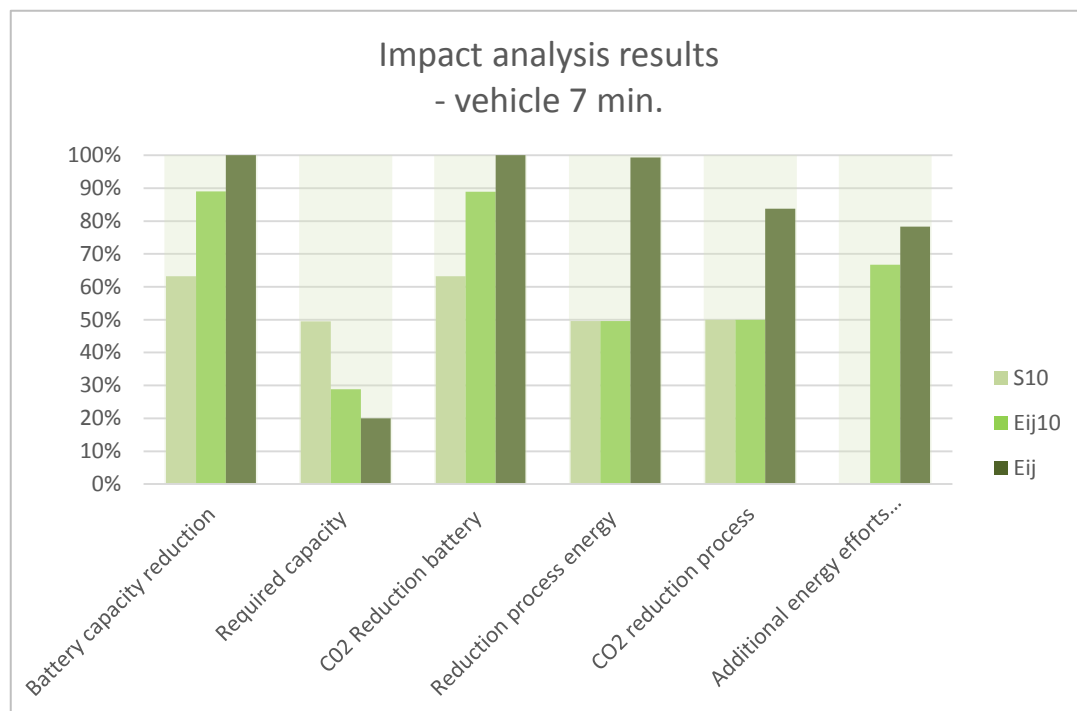


Figure 0-12: Impact analysis results minimum recharging vehicle 7

## Vehicle 8

Vehicle 8 focuses on the component supply with focus on the assembly lines 5 and 4 with average mass of transported goods of 1,100kg. The idle time profile of Figure 0-13 shows a low number of idle time spots alongside the process routes, so that a lower number of break time spots for charging station allocation are subject of consideration.

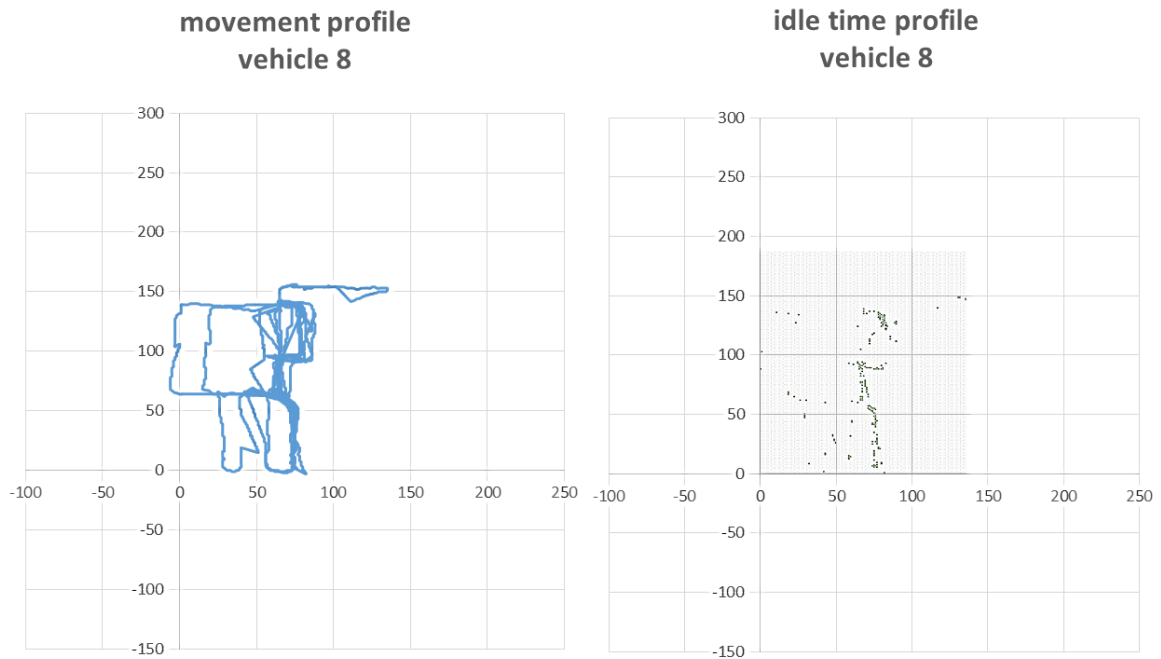


Figure 0-13: Movement (left) and idle time profile (right) vehicle 8

The process data on vehicle 8 shows low total drive distances of average 8,716.94m at an average velocity of 1.59m/s at high values of theoretical charging potential. More detailed investigations have to highlight to what extent these designated idle times can be used for occasional recharging and where optimal charging station allocation determines its location.

Day	Total duration	Process Drive Distance	Average Velocity	Charging potential
	[h]	[m]	[m/s]	[kWh]
⋮				
2	8.00	5,228.72	1.19	26.07
3	8.00	10,472.36	1.65	24.93
5	8.00	11,354.76	2.01	24.87
6	8.00	9,064.93	1.46	25.46
⋮				
<b>average</b>	8.00	8,716.94	1.59	25.55

Table 0-10: Process data vehicle 8

### Location-allocation – vehicle 8

Day based charging station allocation focuses on a part of the production facility in the area between (70/110) to (80/135). Other allocations show no designated distribution pattern, so that allocations of  $S_{10}$ ,  $E_{ij10}$  and  $E_{ij}$  roughly correspond. The determination of the most beneficial charging station allocations is executed within evaluation steps of the subsequent simulation and impact analyses.

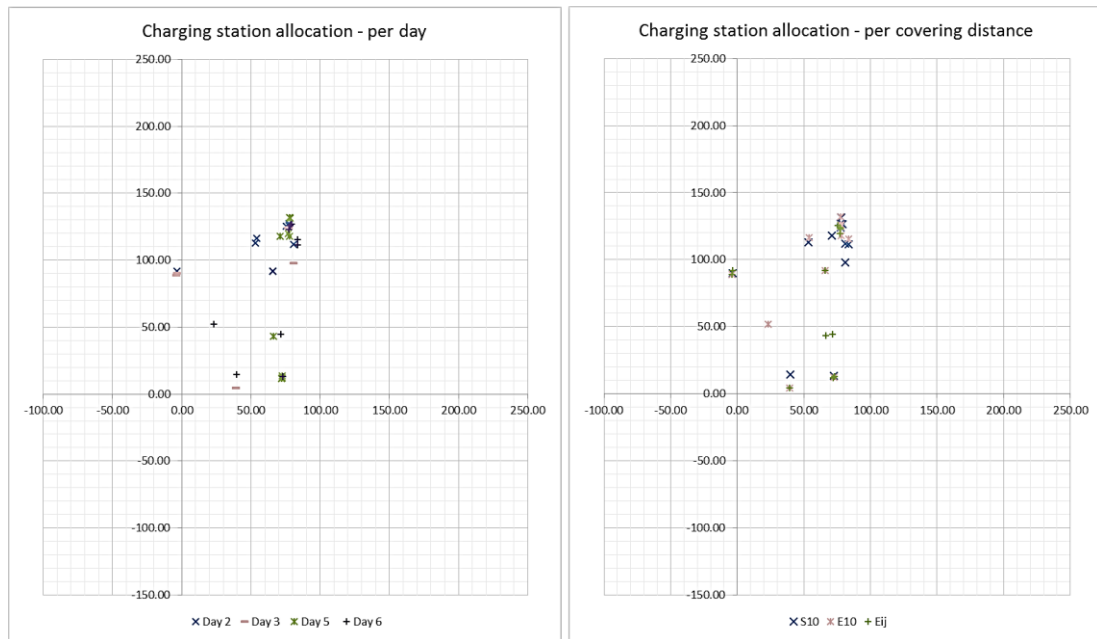


Figure 0-14: Charging station allocation vehicle 8 - per day (left); per covering distance (right)

### Simulation results – vehicle 8

The examination of the total of the recorded days as listed in Table 0-11 shows the minimal recharge energy of  $S_{10}$  to be 8.26kWh, whereas the OCLSM based charging station allocation increases the rechargeable energy to 14.21kWh respectively 16.63kWh. These numbers illustrate the increase of additional recharge energy from  $S_{10}$  to  $E_{ij10}$  for +41.85% and to  $E_{ij}$  for another +14.55%, so that the increase from  $S_{10}$  to  $E_{ij}$  is numbered by 50.31%.

Day	Charging potential	Static charging potential $S_{10}$	Practical charging potential $E_{ij10}$	Additional drive distance	Practical charging potential $E_{ij30}$	Additional drive distance
	[kWh]	[kWh]	[kWh]	[m]	[kWh]	[m]
⋮						
2	26.07	9.13	15.14	363.05	17.01	462.06
3	24.93	8.86	17.46	547.65	17.72	597.44
5	24.87	15.39	19.66	368.84	22.30	850.12
6	25.46	8.26	14.21	503.78	16.63	705.29
⋮						
<b>average</b>	25.55	11.74	17.84	440.77	19.60	644.46

Table 0-11: Simulation results vehicle 8

The increasing numbers of recharge energy from  $S_{10}$  to  $E_{ij}$  again is characterised by a constant development, i.e. ratio. The case study of vehicle 8 shows, that with an increasing amount of recharge energy in reference to the different covering distance definitions, the additional drive distances and by this energy efforts increase in the same ratio. This proportional increase of additional recharge energy to additional drive distance indicates that the maximum downsizing potential can be achieved as the impact from additional drive distance has shown to be comparably low to the system energy balance in reference to the additional energy input.

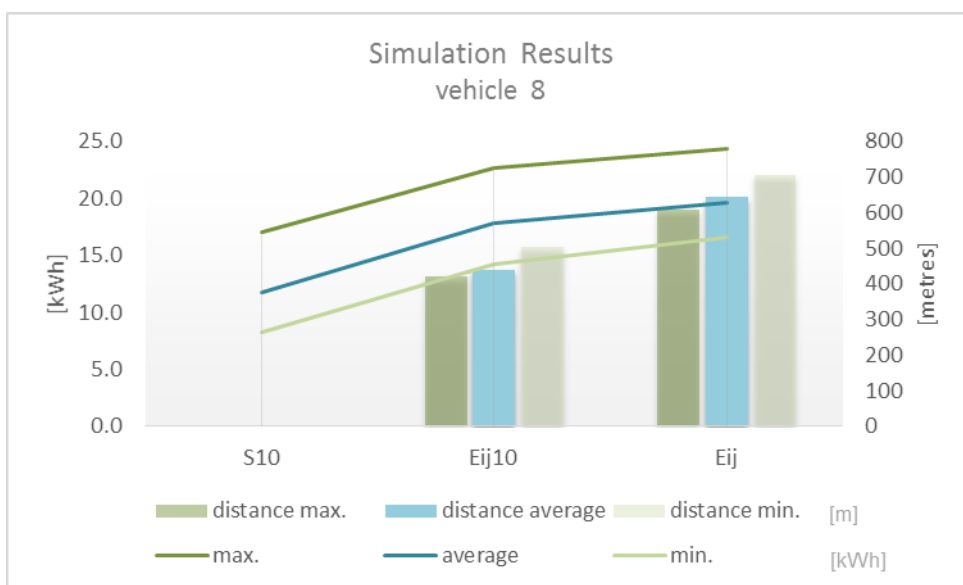


Figure 0-15: Simulation results vehicle 8

### Impact analysis – vehicle 8

The results of the analysis on vehicle 8 according to Table 0-12 show that the maximum potential for system downsizing is achieved by all covering distance definitions. The previous simulation results (see Table 0-11) imply an increase of the recharge energy in reference to the different covering distance definitions, but due to the process structure, its inherent process and idle time profiles and the associated process energy consumption, an increase in recharge energy over the determined value of 8.12kWh does not result in further efficiency improvement based on battery adaptations.

Day	Battery capacity reduction	Required capacity	CO2 Reduction battery	Reduction process energy	CO2 reduction process	Additional energy efforts movement	Additional energy efforts movement	Transmission losses
S <sub>10</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
2	15.74	3.94	1,180.80	4.73	0.064	x	x	1.00
3	15.74	3.94	1,180.80	4.73	0.250	x	x	0.97
5	15.74	3.94	1,180.80	4.73	0.458	x	x	1.69
6	15.74	3.94	1,180.80	4.73	0.110	x	x	0.91
⋮								
average	15.74	3.94	1,180.80	4.73	0.318	0	0	1.79

E <sub>ij10</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
2	15.74	3.94	1,180.80	4.73	0.064	6.94	0.16	1.67
3	15.74	3.94	1,180.80	4.73	0.250	5.23	0.47	1.92
5	15.74	3.94	1,180.80	4.73	0.458	3.25	0.53	2.16
6	15.74	3.94	1,180.80	4.73	0.110	5.56	0.22	1.56
⋮								
average	15.74	3.94	1180.80	4.73	0.25	4.81	0.37	2.07

E <sub>ij</sub>	[kWh]	[kWh]	[kg]	[%]	[kg/day]	[%]	[kWh]	[kWh]
⋮								
2	15.74	3.94	1,180.80	4.73	0.064	8.84	0.20	1.87
3	15.74	3.94	1,180.80	4.73	0.250	5.70	0.51	1.95
5	15.74	3.94	1,180.80	4.73	0.458	7.49	1.23	2.45
6	15.74	3.94	1,180.80	4.73	0.110	7.78	0.31	1.83
⋮								
average	15.74	3.94	1,180.80	4.73	0.318	7.82	0.88	2.14

Table 0-12 Impact analysis results vehicle 8

Referring to the illustration of Figure 0-16, this case study highlights the S<sub>10</sub> charging station allocation for the given process and research environment investigation to be the best solution. As the downsizing and by this process energy and CO<sub>2</sub> saving potentials due to battery downsizing are equal for all three definitions, the further increase in recharge energy by E<sub>ij10</sub> and E<sub>ij</sub> result in ad-

ditional energy efforts for planar vehicle movement. As the optimisation potentials are equal, the lower, i.e. non-existent additional energy efforts of  $S_{10}$  as well as the associated  $CO_2$  emissions within the process operations support this evaluation.

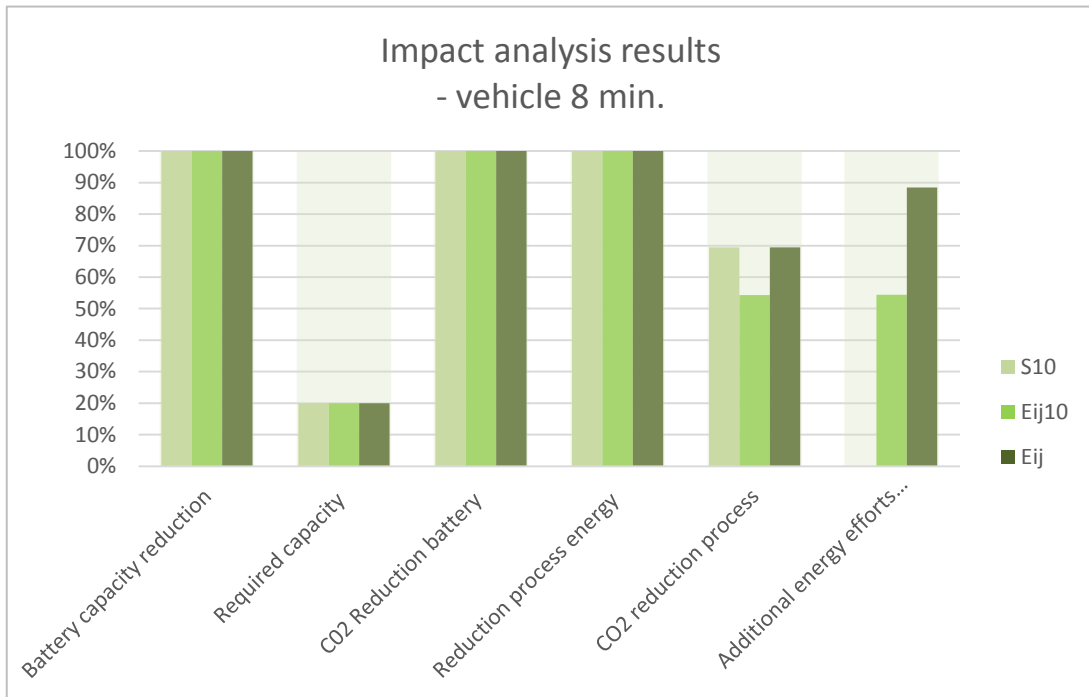
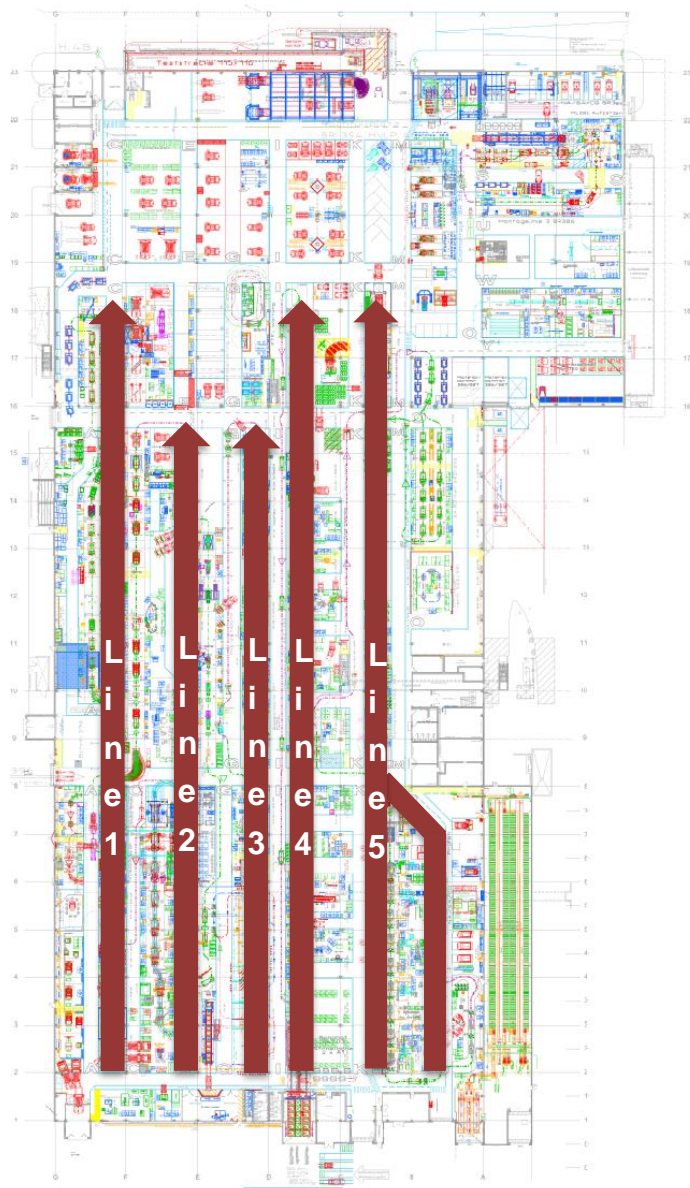


Figure 0-16: Impact analysis results vehicle 8

Appendix G - Case study facility layout





**Appendix H - Publication 1**

Fekete, P., Martin, S., Kuhn, K. and Wright, N. (2014) 'The status of energy monitoring in science and industry by the example of material handling processes'. *Business, Management and Education* (12), 213-227

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**Appendix I - Publication 2**

Fekete, P., Martin, S., Kuhn, K. and Wright, N. (2015) 'Kontaktlose Energieübertragung im produktionsbezogenen Warentransport – Prozess- und Standardverbrauchsanalysen als Grundlage zur Bewertung von Integrationspotentialen'. *Horizonte* (45), 14-16

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**Appendix J - Publication 3**

Fekete, P., Lim, S., Martin, S., Kuhn, K. and Wright, N. (2015) 'Combined energy and process simulation to foster efficiency in non-automated material handling system design'. *Studies in Engineering and Technology* (3), 28-39

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**Appendix K - Publication 4**

Fekete, P. and Martin, S. (2016) *An approach to potential evaluation of contactless energy supply infrastructure for occasional recharging in production related, non-automated material handling*. Unpublished poster presentation at 'CU Research Symposium'. Held 24 February 2016 at Coventry University

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**Appendix L - Publication 6**

Fekete, P., Martin, S., Kuhn, K. (2016) Potentiale kontaktloser Batterieladung im führergesteuerten Materialfluss. Potentials of contactless battery recharging in man-guided material handling. 'Stuttgart Research Forum'. Held 12 May 2016. Stuttgart, Germany

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**Appendix M - Publication 7**

Fekete, P., Martin, S., Kuhn, K. and Wright, N. (2016) *Contactless energy supply for occasional recharging in production related, non-automated material handling*. 'Energy Systems Conference'. Held 14 and 15 June 2016. London, United Kingdom

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**Appendix N - Publication 8**

Fekete, P., Lim, S., Martin, S., Kuhn, K. and Wright, N. (2016) 'Improved energy supply for non-road electric vehicles by Occasional Charging Station Location Modelling'. Elsevier Energy (114), 1033-1040

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## Appendix O - Ethical Approval

Integration of Wireless Power Transfer systems to man-guided material handling processes

P29631

### REGISTRY RESEARCH UNIT ETHICS REVIEW FEEDBACK FORM

(Review feedback should be completed within 10 working days)

**Name of applicant:** Patrick Fekete .....

**Faculty/School/Department:** [Faculty of Engineering and Computing] Post Graduate

**Research project title:** Integration of Wireless Power Transfer systems to man-guided material handling processes

Comments by the reviewer

<b>1. Evaluation of the ethics of the proposal:</b>	
<b>2. Evaluation of the participant information sheet and consent form:</b>	
n/a	
<b>3. Recommendation:</b>	
(Please indicate as appropriate and advise on any conditions. If there any conditions, the applicant will be required to resubmit his/her application and this will be sent to the same reviewer).	
<input checked="" type="checkbox"/>	Approved - no conditions attached
<input type="checkbox"/>	Approved with minor conditions (no need to re-submit)
<input type="checkbox"/>	Conditional upon the following – please use additional sheets if necessary (please re-submit application)
<input type="checkbox"/>	Rejected for the following reason(s) – please use other side if necessary
<input type="checkbox"/>	Not required

**Name of reviewer:** Anonymous.....

**Date:** 23/12/2014.....