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Energy Efficiency Benchmarking-Concepts for Material Flow Systems

Investigations on automated storage and retrieval systems
(*classification, indicator-models, measurement cycles/methods*)

MASTER'S THESIS

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Abstract

This master's thesis deals with the determination and evaluation of the energy efficiency of fully automatic storage and retrieval systems. The continuing rise in the average temperature of the Earth's climate system, rising energy costs and the growing demand for environmentally responsible designed products even in the field of intralogistics led to a research project called effMFS at the Institute of Logistics Engineering at the University of Technology, Graz.

The research project analyzes three types of AS/RS, in particular miniload systems, horizontal carousel systems and shuttle systems, regarding their comparability in terms of energy efficiency. Due to the fact that a direct comparison of several systems has never been done on a scientific level, a basic benchmarking procedure is to be elaborated.

In a first step, this paper describes the fundamental theory of these systems in order to characterize the most important parameters of each system and to find a common base in the vast amount of system specifications, which enables and assures comparability. Furthermore, an excerpt of literature and current scientific research dealing with energy efficiency is presented.

Based on the findings, several energy efficiency indicator models are derived. These models are in accordance with the already acquired knowledge of the effMFS project, which confronts the energy demand with the logistical performance of the systems. To evaluate the energy demand, a standardized guideline is elaborated, that benchmarks the system's power usage over time during a pre-defined representative operating cycle. This cycle includes a load spectrum that consists of several operating states (full load, partial load and standby) as well as specific reference points (storage compartments), that have to be approached by the S/R machines during the benchmarking process. The reference points were derived using standardized guidelines, that were taken out of literature, or using real-life data and are defined as positions, that resemble the mean cycle times for double cycles.

Finally a step-by-step procedure for a proper measurement is described and some boundary constraints as well as environmental conditions are proposed.

Kurzfassung

Die vorliegende Masterarbeit befasst sich mit der Bestimmung und Evaluierung der Energieeffizienz von vollautomatischen Lagersystemen. Der anhaltende Anstieg der mittleren Temperatur im Klimasystem der Erde, steigende Energiekosten und der Bedarf nach umweltfreundlichen Produkten auch im Bereich der Intraglogistik hat am Institut für Technische Logistik an der Technischen Universität Graz zum Forschungsprojekt effMFS geführt.

Das Forschungsprojekt untersucht und vergleicht im speziellen drei verschiedene Lagersysteme hinsichtlich deren Energieeffizienz: Regalbediengeräte, Horizontale Karusselllager (Umlauflager), sowie Shuttle Systeme. Da ein direkter Vergleich von mehreren Systemen zuvor noch nie wissenschaftlich untersucht wurde, wird ein grundlegender Bewertungsprozess erarbeitet.

In einem ersten Schritt werden die theoretischen Grundlagen zu den oben genannten Systemen erörtert um die wichtigsten Parameter zu bestimmen bzw. um eine einheitliche Basis in der großen Menge an unterschiedlichen Systemausprägungen zu finden, die eine Vergleichbarkeit ermöglichen und sicherstellen. Zudem werden bestehende Konzepte aus der Literatur sowie gegenwärtige Forschungsprojekte präsentiert, die sich ebenso mit Energieeffizienz von vollautomatischen Lagersystemen beschäftigen.

Basierend auf den Erkenntnissen werden Energieeffizienzmodelle erstellt. Diese Modelle stehen im Einklang mit dem bereits erarbeiteten Wissen aus dem effMFS Projekt, welches den Energiebedarf der logistischen Leistung des Systems gegenüberstellt. Um den Energiebedarf zu evaluieren, wird ein standardisierter Leitfaden eingeführt, der die Leistungsaufnahme des Systems über die Zeit während eines vordefinierten repräsentativen Arbeitsspiels erfasst. Dieses Arbeitsspiel beinhält ein Lastkollektiv, welches aus mehreren unterschiedlichen Betriebszuständen besteht (Volllast, Teillast und Standby) und speziellen Referenzpunkten (Lagerplätzen), die von den Bediengeräten angefahren werden müssen. Die Referenzpunkte werden mit Hilfe von Richtlinien aus der Literatur oder unter Zuhilfenahme von Echtdaten aus in Betrieb befindlichen Kundenanlagen hergeleitet und spiegeln Positionen wieder, die die mittlere Spielzeit von Doppelspielen darstellen.

Schließlich wird ein schrittweises Verfahren für die ordnungsgemäße Messung beschrieben, sowie einschränkende Rand- und Umweltbedingungen vorgeschlagen.

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1 Introduction

1.1 Initial situation and relevance

One of the biggest concerns society is struggling with is global warming. The continuing rise in the average temperature of the Earth's climate system is not a new topic at all. Beginning in the 1960's, first discussions were held on an international basis. By 1980, a scientific consensus was reached and first political actions, like the establishment of the Intergovernmental Panel on Climate Change (IPCC), were taken.

Today the debate on the climatic change is still ongoing, which has led to a growing awareness of the problem within society. Precisely this current public dispute strengthens the demand for environmentally responsible designed products as well as the establishment of basic approaches leading to an increase in energy and resource efficiency. ([JSR11], p. 4)

In order to fulfill all the goals of ambitious climate protection programs, every single field of industry is in great demand to contribute. ([Gün09]) first addressed this topic by talking about the energy consumption of transport and logistics and possible solutions and potentials to overcome this problem. Of particular interest is the portion which is causes by intralogistics[1]. Beside ecological goals other motivations for being energy efficient do exist. Because of the stringency of fossil fuels and in view of rising energy costs being "green" represents a substantial saving in costs. According to ([Bra11], p. 6) and ([Gün09], p. 6) the costs for intralogistics within a highly-automated distribution center are approximately a quarter (24%) of the total amount spent for external transport and internal logistics. Out of this share, 48% of the total energy costs can be assigned to materials handling technology, storage techniques and picking procedures, further 35% are used for heating and ventilation, and 15% are spent to illuminate the building. The high energy consumption of material handling systems is due to the fact that these systems operate a very large amount of different electrical devices. While the total energy demand accounts for up to 50% of the costs, the electricity requirement per square meter of a given distribution center sums up to one third of the total requirement (see also Figure 1). ([SMZ12], p. 1) "The absolute energy need of a warehouse or logistics center respectively depends particularly on the size of the hall, the throughput, and the degree of automation." ([SMZ12], p. 1)

Until now only little knowledge about possible potentials to reduce the energy consumption in intralogistics was available. Furthermore there "are no standards available to calculate or measure characteristic energy efficiency indicators for MFS [material flow systems, annotation author]. The available standard methods for determining losses and efficiency meet only single components like electric drives (EN 60034)." ([HL12], p. 1)

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[1] "Intralogistics describes the internal flow of materials between different logistics nodes in a company - from materials handling in the production process to distribution centers […] - as well as to the corresponding flow of information." ([CeM])

On account of this, a large number of research projects are currently conducted that contribute in developing technological and technical measures in order to raise energy efficiency. This master's thesis is part of one of these research project titled "*effMFS*[2]". In collaboration with the Austrian Research Promotion Agency (FFG) and the industrial partner SSI Schäfer PEEM GmbH, standards for benchmarking the energy consumption of material flow systems in relation to their logistic operation shall be developed.

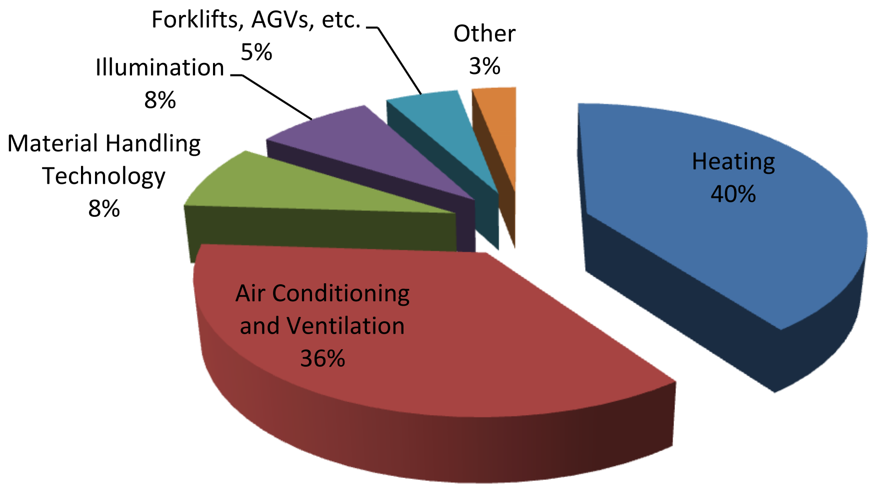

Figure 1: Energy needs structure of an average-automated logistics center ([SMZ12], p. 2)

1.2 Conceptual formulation

1.2.1 *EffMFS* research project

Until now research projects that dealt with energy consumption concentrated on finding solutions to traditional external transport problems. These findings cannot easily be transferred to intralogistics as the nature of these processes is completely different. Furthermore, the already mentioned lack of standard methods to quantify possibilities of energy conservation by doing calculations, simulation or measurement led to the application for funds. The primary focus of the *effMFS* research project can be divided into two parts. First of all, possibilities of increasing energy efficiency in general shall be derived. As the experimental field mainly concentrates on mechanical conveyor systems their electric drivetrains, designs and control strategies are of particular interest. Possible potentials like ecologically worthwhile energy efficient electric drives or optimization through minimization of friction losses shall be revealed. Secondly, a general comparison of material flow systems that is completely independent from any manufacturer or technical principle shall be developed. ([LHJ13], p. 1) Since mechanical conveyor systems are only one sub-category of intralogistics, the *effMFS* project is to be expanded to automated storage systems based on already elaborated definitions of energy efficiency.

[2] Abbreviation for „Energy efficient material flow systems“

1.2.2 Research questions

This master's thesis aims at developing basic principles and methods of valuation regarding the energy efficiency of automated storage and retrieval systems. The quantification of the efficiency shall be achieved via the use of indicator models and standardized guidelines on how to perform a measurement. In order to achieve this goal, the following research questions have to be answered:

- Which concepts of energy efficiency indicator models do already exist in literature?
- For which type of automated storage and retrieval systems are theses existing models valid?
- What are the relevant parameter and operating conditions (load cycles) of each examined automated storage and retrieval systems (stacker crane, horizontal carousel, shuttle system (also called autonomous vehicle storage and retrieval system))?
- Is there a possibility to define a general working cycle that is applicable to all three examined automated storage and retrieval systems?
- Which requirements have to be defined in order to define a generally accepted indicator model?
- How can a set of theoretical regulations be transferred to a real measuring technique?
- How can the appropriate energy efficiency indicator be calculated?
- Which indicator can be derived from the test bench at the Institute of Logistics Engineering?

1.3 Approach

In order to enable a comparable declaration of energy efficiency, a tangible value has to be derived that contrasts all automated storage and retrieval systems from every manufacturer regarding their energy consumption and logistical output with each other. Until now a certain efficiency ratio could easily be stated since all information was either based on non-standard calculations or simply marketing. The special indicator, that shall be developed in this thesis, enables a quick and easy comparison which system is capable of supplying the same logistical output but with less energy. This can only be achieved by developing a comparable, and if possible real-life working cycle that is applicable to all three automated storage and retrieval systems (stacker crane/miniload system, horizontal carousel system, shuttle system). On account of this, the first task of the thesis was to get one's eye into the different functions of the mentioned AS/RS. Furthermore, all approaches quantifying energy efficiency in intralogistics that already exist in literature are of particular importance. Although the vast majority of the effMFS research project is already well-known due to participation as scientific staff member and study assistant, it is still necessary to get acquainted with the regulations regarding system boundary conditions and valuations principles that are resolved together with the help of the steering committee of the project. Last but not least, a familiarization with the existing AS/RS and measurement system at the Institute of Logistics Engineering is necessary. Based upon this information, a standardized working cycle is developed. The obtained results in the form of energy efficiency indicators are proposed to the comity of the effMFS research project.

1.4 Terminology

In order to clarify some conceptions that are used throughout the thesis and the effMFS research project, this section covers some definitions.

1.4.1 Automated storage and retrieval systems

“Automated Storage and Retrieval Systems (AS/RS) are warehousing systems that are used for the storage and retrieval of products in both distribution and production environments.” ([RV08], p. 1)

Unfortunately, this definition is not always used consistently in literature as well as in the material handling industry. In this thesis the term AS/RS is used to refer to a whole category of storage systems that can also be described as fully automatic storage systems. In particular stacker cranes, horizontal carousel systems and shuttle systems shall be subsumed under the term AS/RS.

1.4.2 Energy efficiency

A ratio between an output of performance, service, goods or energy, and an input of energy. ([Eur06], p. 67)

In mechanical engineering the definition of efficiency is characterized by the ratio of an output compared to the necessary input.

$$\eta = \frac{Output}{Input} \leq 1$$ Equation 1

In the effMFS research project this definition is to be expanded and transferred to the definition of energy efficiency, which shall be a ratio of a “general definable output of performance, service, goods or energy, depending on the application, and is set to an input of energy”. ([LHJ13], p. 2)

$$Energy\ efficiency = \frac{Output\ of\ a\ performance\ or\ process}{Input\ of\ energy}$$ Equation 2

According to ([LHJ13], p. 3), it is recommended for intralogistics to use a combination of several basic parameters as the output of a logistical process, that refer to a “logistic performance”.

$$E_{eff} = \frac{W_L}{E_E}$$ Equation 3

1.4.3 Specific energy demand

Further it is beneficial to introduce a specific energy demand of a process by taking the reciprocal value of the energy efficiency, since specific values are more common in the field of mechanical engineering.

$$Specific\ energy\ demand = \frac{1}{Energy_{efficiency}} \quad \text{Equation 4}$$

$$E_C = \frac{1}{E_{eff}} = \frac{E_E}{W_L} \quad \text{Equation 5}$$

1.4.4 Logistic performance as a reference value

The definition of the reference value “logistic performance” is not straightforward. As a matter of principle it has to represent the benefit that has been generated with the input of energy. ([Deu12]) lists a couple of reference values that are common static or dynamic warehouse key figures, which turn out to be of limited usability to represent processes that can be found in automated storage and retrieval systems. (Cf. [SFB13b], p. 191) Therefore it is inevitable that one or more reference values are defined in such a way that they include the requirements and system specifications of an AS/RS. Examples to be mentioned are the throughput, nominal payload, dimensions of unit loads, capacity/number of storage locations or the power-on hours of the AS/RS. (Cf. [SFB13b], p. 200) The considerations and final definition of the logistic performance are described in chapter 3.

1.4.5 Throughput

> *The throughput is defined as the mean unit load flow in to [sic!] and out of the warehouse. It is measured in transport units per hour (TE/h) [UL/h, author’s note]. Depending on the type of operation, we differentiate between the "input rate" (QE) the "output rate" (QA) and the "combined throughput" (QK). All three types can be regarded as throughput. This is determined in accordance with the requirements of the storage system. ([VDI98], p. 3)*

1.4.6 Storage ratio

The storage ratio is defined as the ratio of allocated storage compartments to the total number of locations (storage capacity). (Cf. [tH11], p. 170)

1.4.7 Utilization degree

The utilization degree is a ratio of the actual value to the maximum of any base ([tH11], p. 209). Also used to express the quotient of the total volume consumed by all unit loads to the total volume of the storage system. ([tH11], p. 284)

2 Basic Principals

2.1 Automated Storage and Retrieval Systems

Beginning in the 1950s, automated storage and retrieval systems have been used widely as a storage solution in intralogistics. Different types of AS/RS do exist, but in general these systems are built to be fully automated which means that handling of any load can be done without the need of an operator. Compared with other technologies, AS/RS have several distinct advantages over non-automated systems. Less error rates, increased reliability, a huge potential in saving labor costs and floor space as well as an improved material flow and improved inventory control[3] are just a few to be named. Both in production and distribution environments the main task of an AS/RS is to fulfill orders that are either putting products in storage or retrieving those products from storage again. The storage and retrieval process as core function can be used in various settings. In general AS/RS systems are defined as storage systems that use fixed-path storage and retrieval machines. Main components of AS/RS are cranes or vehicles, high-bay racks and its aisles, Input/Output (I/O) points, conveyors and pick positions. ([RV08], p. 1)

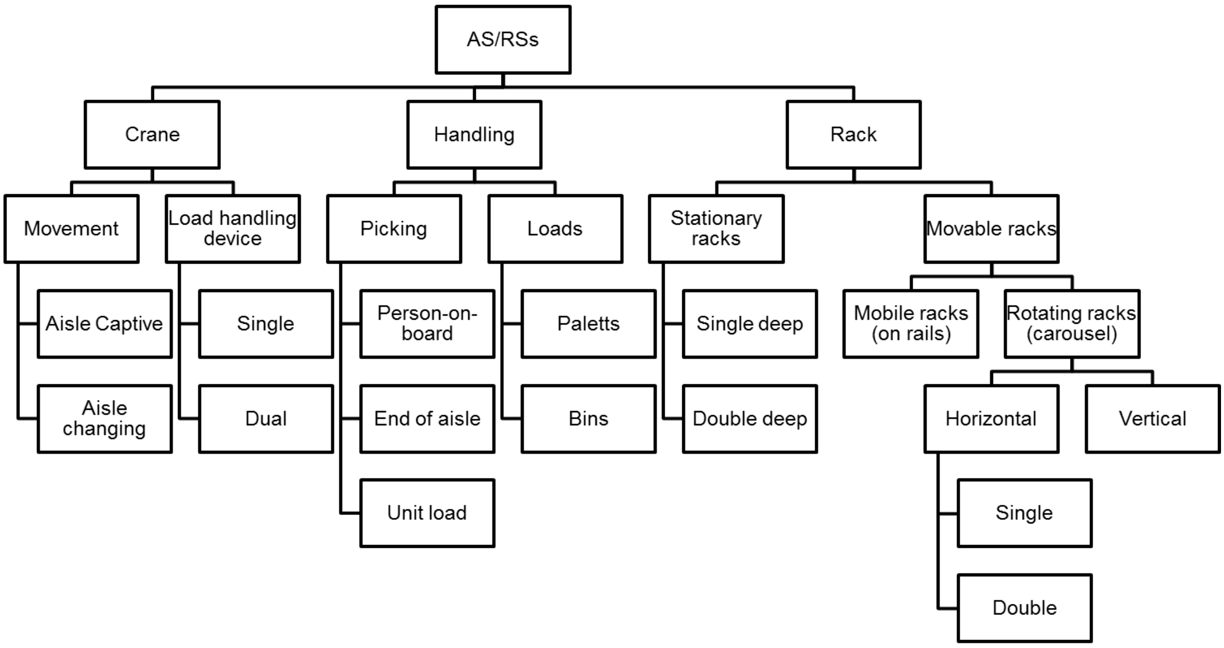

Figure 2: Classification of various AS/RS system options[4]

The centerpiece of any AS/RS is of course the crane or vehicle that is the fully automatic storage and retrieval machine, which enables the movement, picking and dropping of loads. High-bay racks are constructed using a metal structure that provides storage locations, that can accommodate the load, that is intended to be stored. In general a storage aisle is formed

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[3] ([HSG76], p. 629)

[4] Cf. ([RV08], p. 345)

by the empty space between the arrays of high-bay storage racks and provides the place where the rails of the cranes or vehicles are mounted. The I/O point is the location where incoming loads are picked up for storage and vice versa where retrieved loads are dropped off and delivered towards pick positions. These pick positions are work places where people remove or add individual items from a retrieved load that is then fed back into the storage system again. Figure 2 provides a good overview of all system options that exist for AS/RS.

2.2 AS/RS design

The final physical configuration as well as the programming and control policy of any automated storage and retrieval system strongly depends on the underlying performance needs. This is often expressed in terms of the necessary transshipping performance or the storage capacity requirements. Table 1 lists an overview of some possible system configuration parameters that can be varied when configuring an AS/RS. Figure 4 shows all kinds of influencing factors and focuses mainly on control policies. Each parameter that is listed in either the table or the figure is described in the following chapters in more detail in order to understand the basic principles of AS/RS.

Figure 3: Correlation of the AS/RS system configuration, control policies and logistical performance[5]

Table 1: Overview of import parameters of automated storage and retrieval system configuration[6]

AS/RS configuration	AS/RS characteristics			
Rack type	Stationary		Dynamic	
Rack shelf depth	Single deep		Double deep	
Number of load handling devices	1	2	3	4
Width of load handling device/ storage aisle	Single wide		Double wide	
Number of I/O points	1	2	3	4
Location of I/O points	End of aisle		Offset x- or y- axis	
Crane/vehicle movement	Aisle/level captive		Aisle/level changing	

[5] (Cf. [RV08], p. 345; [VTV12], p. 168)
[6] Cf. ([AGU11], p. 11)

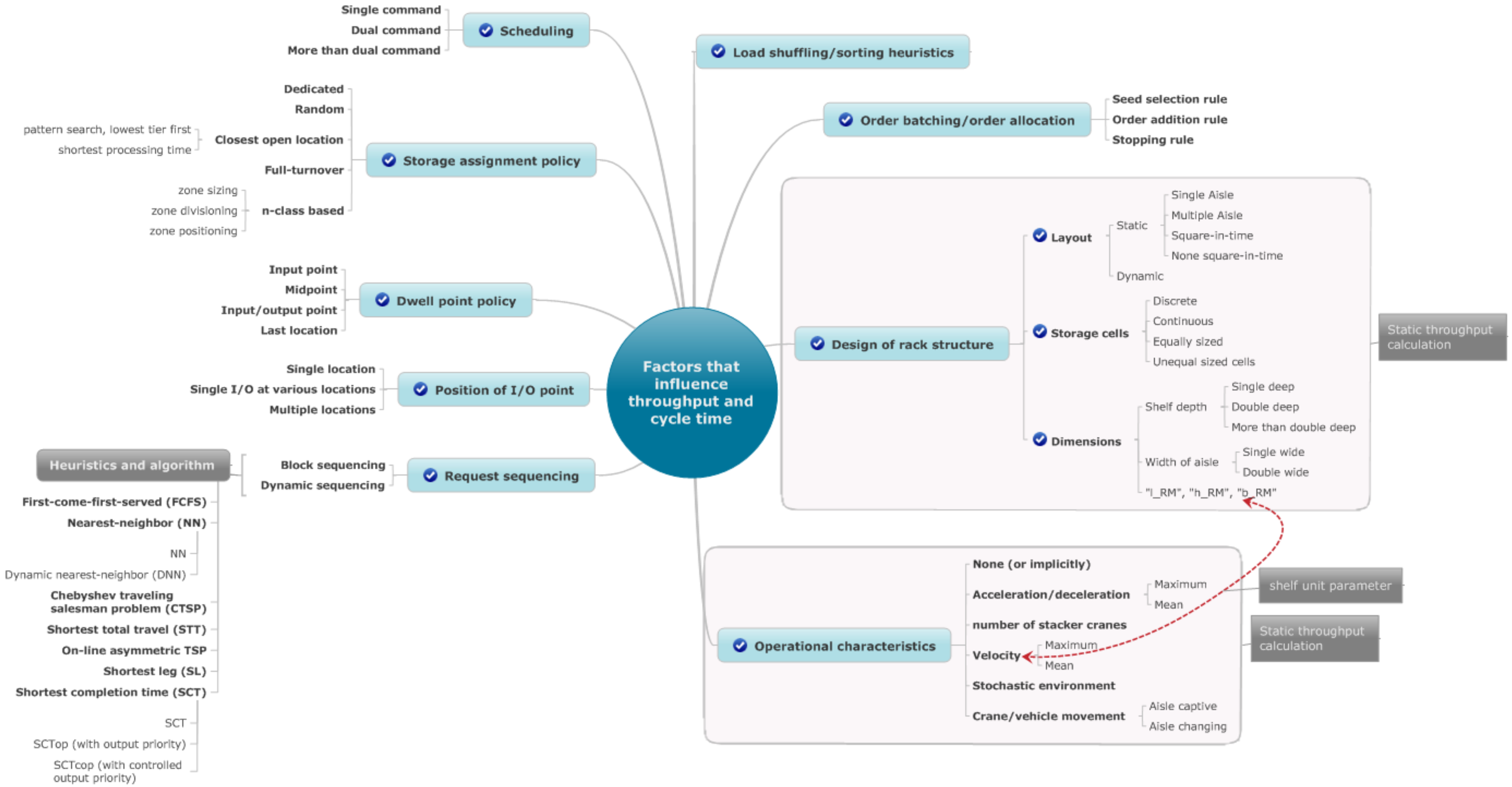

Figure 4: Factors influencing throughput and cycle time of AS/RS[7]

[7] (Basic intention according to[Sch07], p. 60)

2.2.1 Rack types

A warehouse is a very generic term where several different types can be subsumed. A possible classification is listed in ([Arn08], p. 646):

- Functional classification
- Classification according to construction height
- Classification according to fill mass
- Classification according to load carrier
- Classification according to storage media.

For a further consideration the last point is of interest which can be sub-divided into the following classes: ([Arn08], p. 646):

- Ground storage
- Static warehouse (stationary racks)
- Dynamic warehouse (moveable racks)
- Storage on load carrier

As can be seen in Figure 2, AS/RS are constructed using either stationary or moveable racks. These types shall be described in the following.

2.2.1.1 Static warehouse (stationary racks)

The nature of service of a rack is to store goods that cannot be nested. Furthermore, the usable shelf height and its partitions are of importance. The shelf height is defined as the distance between the floor and the top edge of the highest traverse and is within the range of 2 to approximately 50 m. Stationary racks used for AS/RS are typically built as line storage, which means that all storage fields are arranged line by line in order to enable an arbitrary access to all stored unit loads. A storage field is defined as the space within two inner or outer vertical rack frames. Depending on the type of unit load, a storage field can be divided into one or several storage compartments (also bin compartments).

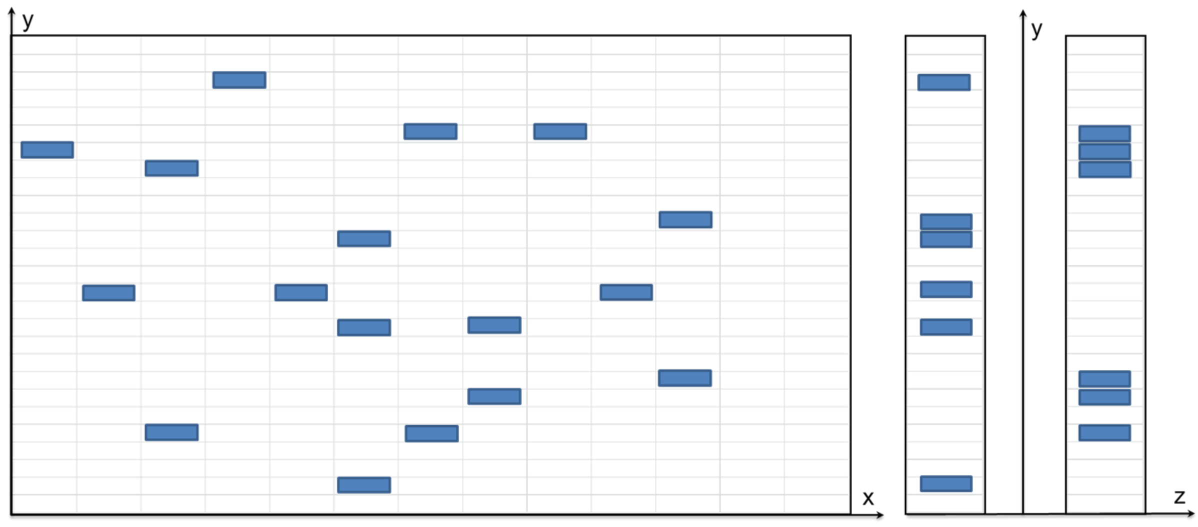

Figure 5: AS/RS (stacker crane) with single wide aisle, single deep racking system

The arbitrary access to each storage compartment is only given if the shelf depth, which is defined as distance between the outer frames edges, is single deep as shown in Figure 5. Single deep storage also enables every type of storage assignment. ([GF11], p. U88; [tH11], S. 170–171)

Considerations concerning the transshipping performance have led to an extended usage of racking systems with increased shelf depth in recent times. Depending on the storage assignment strategy (see also chapter 2.2.3), several unit loads are stored into one storage compartment, which means that the rack is at least double-deep (see also Figure 6). Double deep AS/RS racks essentially consist of two single-deep racks placed one behind the other, and so unit loads are stored in the first and second storage lane. ([BH11], p. 61)

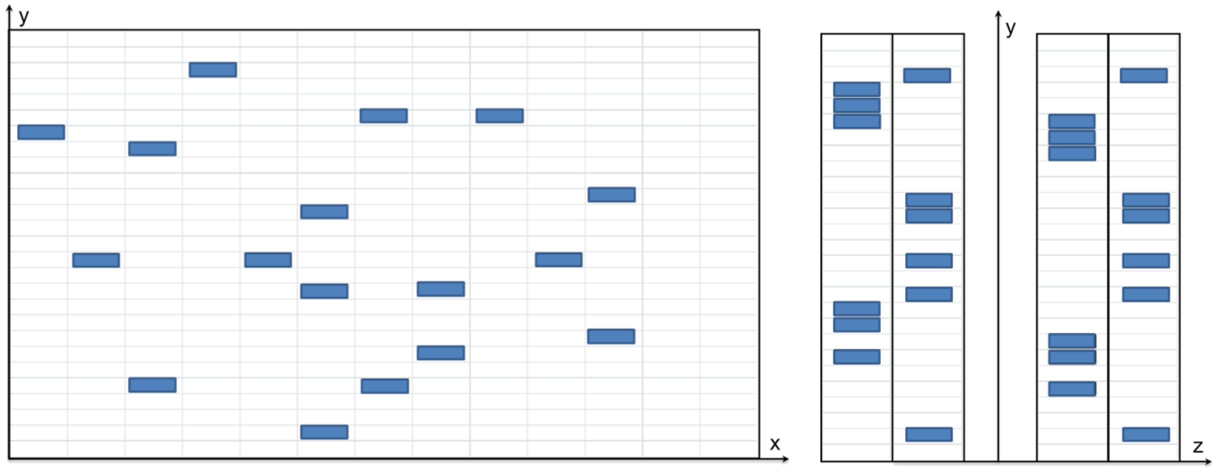

Figure 6: AS/RS (stacker crane) with single wide aisle, double deep racking system

Although double-deep storage has many advantages like an improved utilization degree, it faces great problems if the wrong storage assignment strategy is used. The transshipping performance decreases significantly if a unit load is to be retrieved that is blocked by another unit load in front of it. The re-storage process that is necessary in order to perform the retrieval is very time-consuming as the first unit load has to be picked up and moved to another storage compartment. When planning the operation of a double-deep AS/RS it is also important to consider the cost effectiveness. ([Wol03], S. 8–9)

2.2.1.2 Dynamic warehouse (moveable rack)

The main characteristic of a dynamic warehouse is the movement of each unit load between the storage and retrieval process. The movement can result from either moving the unit loads within the storage field or by moving the complete racking system, which applies to automated storage and retrieval systems. ([Arn08], p. 652)

([GF11], p. U 90) lists the reasons for introducing dynamic storage to AS/RS systems:

- Reduction of travel in order-picking leading to an increase in order-picking performance
- Realization of higher transshipping performance in compact warehouses
- Combining advantages of block and line storage (depending on the type of dynamic storage)

The standard design of a movable racking system for AS/RS is the so called carousel system. It can basically be described as a steady conveyor that has been extended with storage capacity. Every storage field that holds a pile of storage compartments, is connected to a moving conveyor chain. To retrieve a single item, the whole warehouse is moved until the required storage field is in front of the I/O point (see Figure 7).

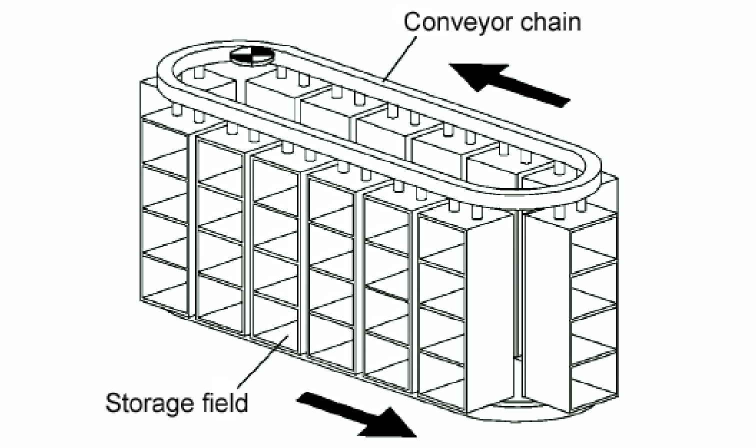

Figure 7: Dynamic warehouse (horizontal carousel system)[8]

2.2.1.3 Square-in-time and none square-in-time (rectangular) racks

The two rack type definitions “square-in-time” and “none square-in-time” were first introduced by ([HSG76]) when the authors introduced a continuous approach in AS/RS travel time models. By definition a rack is called “square-in-time” if the dimensions and the vertical and horizontal speeds of the AS/RS crane/vehicle are such that the time to reach the most distant row (tier) from the I/O station equals the time to reach the most distant bay (column). If there is a difference the rack is simply called “none square-in-time” or “rectangular” rack.

2.2.1.4 Storage Compartments

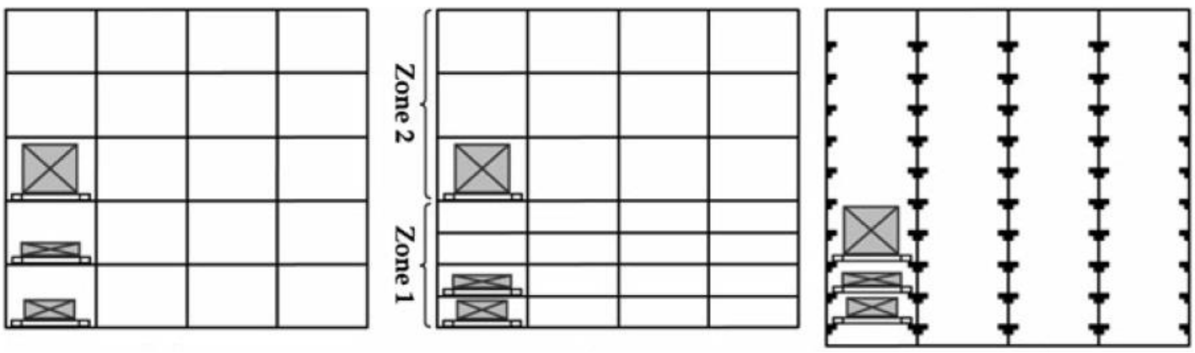

Figure 8: Structure of a rack with equal size, unequal size and modular cells[9]

[8] ([GF11], p. U 92)
[9] ([VTV12], p. 176)

As it can be seen in Figure 8, AS/RS racks can be sub-divided into three different classes. There are racks that feature storage compartments (also called storage cells) of equal size according to the dimension of the unit load that is to be stored in these compartments. This is the most common type of rack, however in terms of flexibility of the storage capacity, an equally sized rack is inefficient, especially if the unit load varies in size and/or type. Therefore models do exist where the rack contains cells which are unequally sized. Each cell is of the same size but differs in height, in order to hold various types of unit-loads. Although this model is more flexible than storage compartments with equal size, it is still inflexible and has a low utilization, especially if there is high fluctuation in terms of unit-load size. Another model proposed by ([LHH05], p. 1), that can be used to overcome the same problem, uses modular cells. The best size of the modular cell is determined as a decision variable.

2.2.2 Capacity of load handling device[10]

In general, a load handling device carries one unit load at a time as depicted in Figure 9. In 1972 Gudehus started to think about load handling devices with enhanced capabilities and thus carrying more than one unit load during a single storage cycle. Gudehus stated that several positive effects are achievable. On the one hand, delivery-time to the storage compartment and on the other hand travel time from position A to position B decreases per load unit if more unit loads can be handled at once. A limitation of 4 load handling devices is reasonable as the technical complexity is higher compared to possible enhancements in terms of performance. ([Vid94], p. 69)

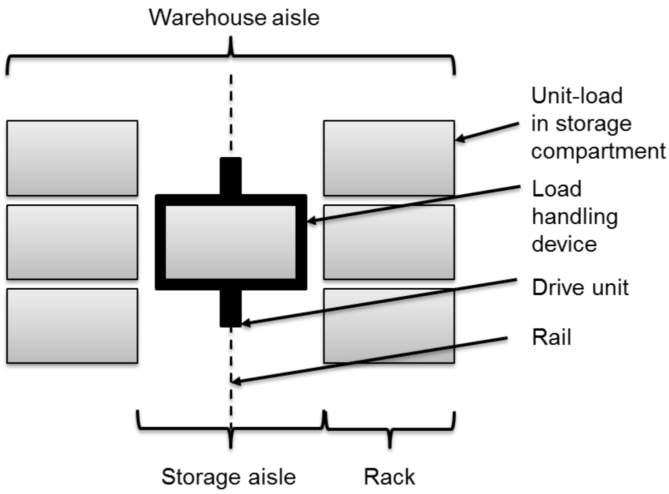

Figure 9: Schematic diagram of single deep rack with single wide load handling device[11]

Independent of the type of the automated storage system the load handling device generally carries the unit loads with its broadside perpendicular to a driven axis. As a result one has to

[10] All schematic diagrams do apply to AS/RS with static rack, but are also valid for dynamic racks (storage compartments on only one side, likewise to the left or right)

[11] (Nach[AGU11], p. 12)

differentiate not only between single or multiple unit loads but also various possible technical implementations:

- Load handling devices that are mounted along the axis of the driving unit (also known as single wide aisle)
- Load handling devices that have several unit loads side by side and/or that are mounted along the axis of the driving unit (also known as double wide aisle)

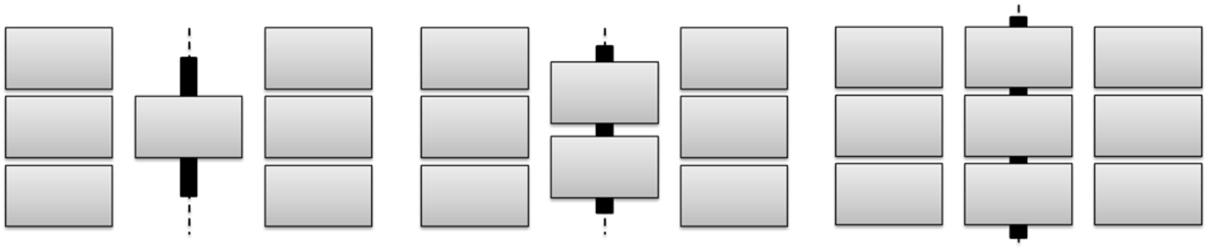

Figure 10: Top view onto 3 different single wide, single deep load handling devices[12]

An example of load handling devices carrying 1 to 3 loads that are mounted along the axis of the driving unit can be seen in Figure 10. If the stationary rack is double deep, as discussed in chapter 2.2.1.1, and if the load handling device has been adapted accordingly, it is possible to store two unit loads into one storage compartment one after another. ([AGU11], p. 13)

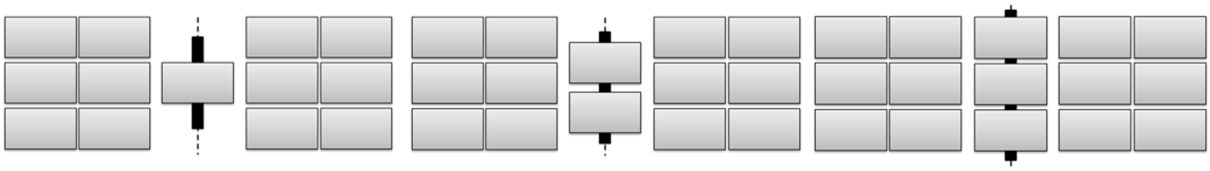

Figure 11: Top view onto 3 different single wide, double deep load handling devices[13]

The main difference between Figure 11 and Figure 12 is the width of the storage aisle. In Figure 11 the load handling device is only single deep while in Figure 12 the load handling device is double deep carrying two unit loads side by side. Since both unit loads can be stored at the same time, a higher transshipping performance at the expense of a lower capacity degree is achievable. This type of load handling device can only be found in small parts storage systems (miniload systems). ([AGU11], p. 14)

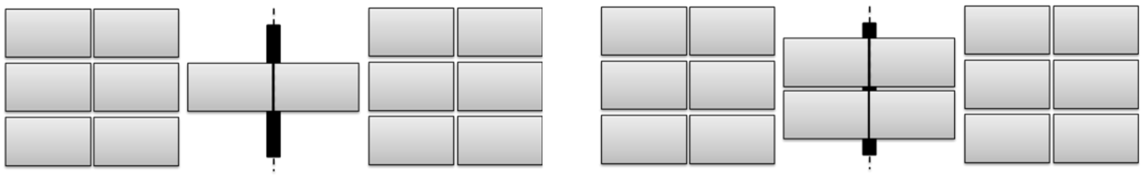

Figure 12: Top view onto 2 double wide, double deep load handling devices[14]

[12] (Cf. [AGU11], p. 13)
[13] (Cf. [AGU11], p. 13)
[14] ([AGU11], p. 14)

2.2.3 Storage assignment strategies

In order to provide an optimal scheduling of automated warehousing systems, it is necessary to implement a set of rules that accomplish the following: ([HSG76], p. 693)

- Assignment of multiple items of different or same type to the same unit load (bin or pallet assignment)
- Assignment of unit loads to an exact location within the high-bay racking (storage assignment)
- Sequencing of storage and retrieval requests (order scheduling)

In literature several different storage assignment policies can be found. The most common are described here in more detail: ([RV08], p. 349)

- Dedicated storage assignment
- Random storage assignment
- Closest open location storage assignment
- Full-turnover-based storage assignment
- Class-based storage assignment

2.2.3.1 Dedicated storage assignment

The dedicated storage assignment rule is the simplest one. Each unit load is assigned to a fixed location. When replenishing the unit load, it is retrieved and stored at the same location as before. This assignment method is very often used in non-automated warehouses, where heavy goods are placed at the bottom of the rack or according to the layout of the warehouse. When used in an AS/RS the disadvantages predominate as it requires very much space but utilizes this space very little. Since all products are assigned to one single location, this location gets reserved even if the product is out of stock which results in a bad utilization. On the other hand, the high space requirement is due to the fact that sufficient space must be provided in order to accommodate all products if none of them is out of stock. ([RV08], p. 349; [tH11], p. 98)

2.2.3.2 Random storage assignment

In contrast to the previous rule, the random storage assignment method is able to assign any unit load to any storage location that is empty. Each empty location has got the same probability that a single unit load is assigned to it. Therefore the necessary storage capacity of the warehouse can be reduced. This effect is even greater the more unit loads have to be stored for each article. The random storage assignment, also called chaotic storage, is the most common strategy used in today's AS/RS systems. The chaotic storage has positive effects on the statics of the racking and achievable transshipping performance. ([tH11], p. 107; [RV08], p. 349; [HSG76], p. 631; [AGU11], p. 24)

2.2.3.3 Closest open location storage assignment

The closest open location storage assignment is similar to the random storage assignment. The later can also be used to approximate the closest open location rule. The basic concept of this strategy is based upon an upstream scan in order to list all open rack positions just before starting to store the next unit load. The unit load is then moved to the location which is closest to the I/O point of the AS/RS and stored there, regardless of the turnover of the article. This assignment leads to non-uniform storage distribution where all locations in the vicinity of the I/O point are full and gradually emptier towards the other end of the racking. A disadvantage of this type of storage assignment is the negative effect of a very high partial storage ratio. This partial agglomeration leads to decreased transshipping performance. ([HSG76], p. 631; [RV08], p. 349; [AGU11], p. 24)

2.2.3.4 Full-turnover-based storage assignment

As the name suggests, this storage assignment strategy is based upon the frequency of demand of a given article within a unit load. The full-turnover-based storage assignment policy states that the more frequently a unit load is requested the easier it should be accessible. This means that these products are stored near the I/O point whereas slow-moving articles get located farther away. The policy necessitates that the turnover frequency of all unit loads needs to be known in advance. In 1963 Heskett introduced the cube-per-order index (COI or CPO) that determines where to store a unit load according to its demand frequency. The COI is defined as:

$$COI = \frac{Required\ storage\ space}{Number\ of\ requests\ per\ period} \qquad \text{Equation 6}$$

The lower the COI the nearer the unit load is located to the I/O point. One of the greatest problems of this approach is the fact that demand frequencies are far from being constant. Any change to the article structure of the warehouse or the demand frequency leads to necessary repositioning of all unit loads so that the storage location coincides with the storage assignment rule again. To prevent excessive repositioning, the recalculation of the COI is done periodically. ([RV08], p. 349)[15]

2.2.3.5 Class-based storage assignment

The repositioning in full-turnover-based storage assignment strategies essentially represents unnecessary effort that should be omitted. The class-based storage assignment rule makes use of the cube-per-order index as well but maintains a higher efficiency. Basically the method divides the available space within the warehouse into a given number of separate zones. Each item is then assigned to an area based upon its demand frequency and its travel time respectively (optional). Within each zone the storage process is carried out randomly again. The class-based storage assignment is widely known under the name of ABC-classification and its corresponding Lorenz-Curve that is depicted in Figure 13.

Fast-moving articles are sub-items of the A-zone, whereas slower moving items are classified accordingly to the B- or C-zone. The increase in efficiency due to the zoning of the products is again realized by simply locating the fast-moving times in the vicinity of the I/O

[15] For a more detailed description of the COI or CPO see ([Gla08], p. 40)

point. At the same time the class-based storage assignment requires less space and is more flexible as the exact location is applied randomly. ([RV08], p. 349; [HSG76], p. 635)

When implementing a class-based storage assignment rule three different parameters have to be considered:

- Determination of the number of zones[16] (zone divisioning)
- Assigning the products to the zone (zone sizing)
- Location of the zone (zone positioning)

In literature, several different procedures on how to derive optimal zone boundaries can be found. Generally speaking many authors distinguish between square-in time racks and conventional rectangular racks on the one hand, while considering a single or dual command cycle strategy on the other hand. Research has shown that a smaller number of zones is to be preferred since it enables savings in travel times. As the name "ABC-classification" suggests, the number of classes are often restricted to three in practice. Positioning of the zones is also dependent on having single or dual command scheduling as well as on the location of the I/O point. In Figure 14 two different possibilities on how to position three zones in a high-bay racking are shown. ([RV08], p. 350)

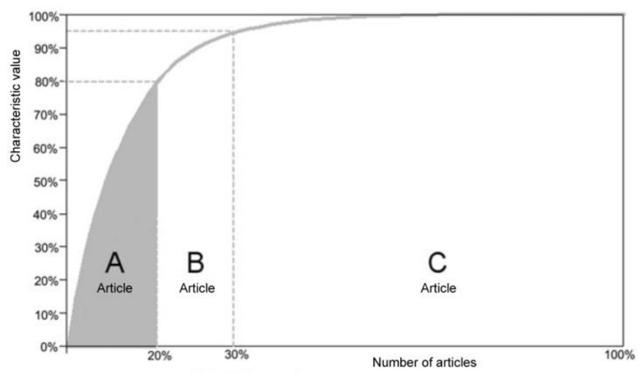

Figure 13: ABC-classification of articles, Lorenz-Curve[17]

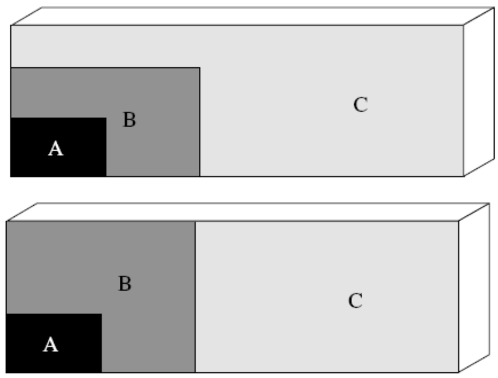

Figure 14: Typical zone positioning for three classes[18]

2.2.4 Scheduling (working cycles in general)

A working or storage cycle is defined as a complete motion-sequence that is performed in order to fulfill a certain logistical function especially storing or retrieving a unit load. A working cycle of an AS/RS typically consists of unloaded driving, positioning, load picking, moving the load, positioning, load drop-off and returning back to the I/O point. Alternatively returning is not part of the working cycle. In this case the automated retrieval machine waits in a

[16] ABC-classification is just one possibility

[17] (According to [tH11], p. 2)

[18] ([RV08], p. 350)

predefined position. In general working cycles are to be distinguished between the following: ([tH11], p. 12)

- Single cycle
- Double cycle
- Cycles with single or double deep storage
- Cycles according to the storage system and unit load

A working cycle also represents the basis to calculate the mean cycle time according to VDI- or FEM guidelines.

2.2.4.1 Single cycle (single cycle command)

A single cycle is used to either store or retrieve a unit load. If an AS/RS is operated in a single cycle mode for storage it starts its motion-sequence beginning with picking up a unit load at the I/O point, moves the item to the desired storage location where the automated retrieval machine has to position precisely, followed by dropping off the load and finally returns to the I/O point again in order to pick up the next unit load. Otherwise if a single cycle mode is used for retrieval the AS/RS starts by heading towards the storage location where the unit load resides. After positioning and picking up, the unit load is moved towards the I/O point. ([tH11], p. 80)

Figure 15: Single cycle operation using the example of a rack feeder

Figure 15 shows an example of a single cycle operation, in which the black arrows represent the storage process and the empty travel back to the I/O point.

2.2.4.2 Double cycle (dual/double cycle command)

Operating an AS/RS in single cycle mode only is quite inefficient since many unloaded movements are necessary. Therefore a double cycle operating mode does exist. In contrast to the single cycle, the AS/RS machine does not return to the I/O point after placing a load into a storage location. It is further moved to the next storage location where another unit load is retrieved and dropped off at the I/O point. ([tH11], p. 66) A double cycle thus combines both storing and retrieving a bin or palette. The sequence of these two sub-processes is dependent on the type of AS/RS. In general a horizontal carousel system first retrieves an item in order to store the next unit load into the same storage compartment, whereas a conventional stacker crane first stores and then retrieve a unit load. If the load handling device is capable of carrying several unit loads, as discussed in chapter 2.2.1.3, a double cycle can consist of multiple storage and retrieval processes. ([Rit03], p. 18)

Figure 16 shows an example of a double cycle operation, in which the black arrow represents the storage process, the blue arrow the empty travel towards the next storage compartment and the green arrow the retrieving process.

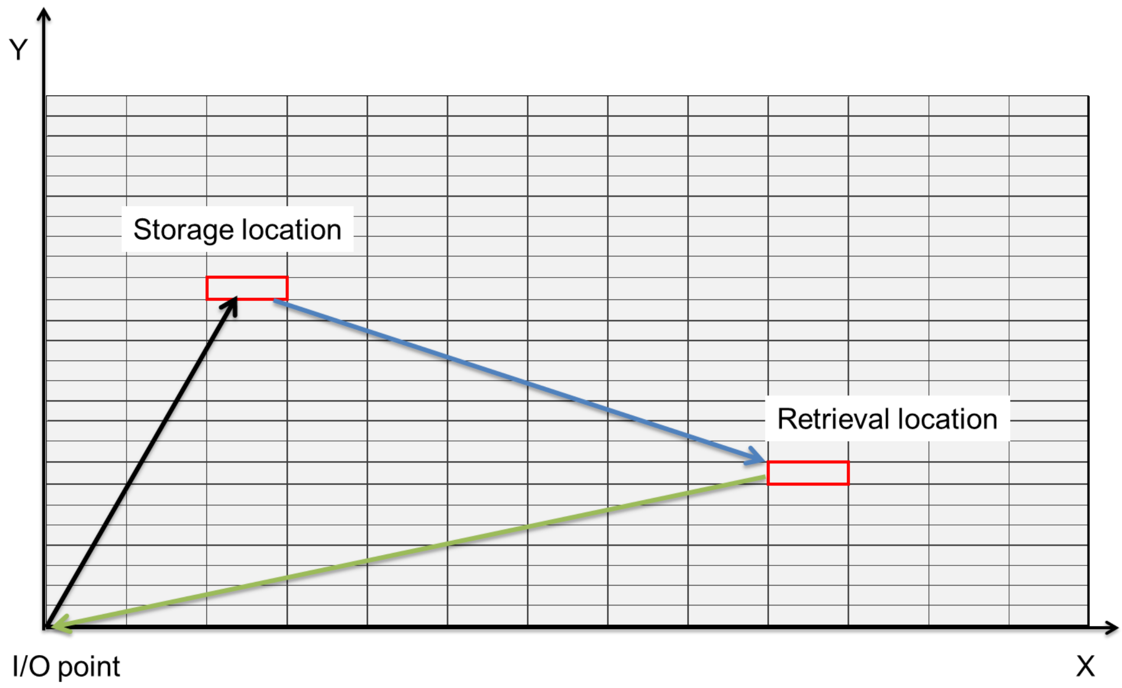

Figure 16: Double cycle operation using the example of a rack feeder

2.2.4.3 Cycle time

The cycle time is defined as the time needed to complete a single or double cycle. The cycle time always consists of both constant and variable time slices. These time slices strongly depend on the desired travel distance to the storage compartment as well as the technical specification, especially the maximum acceleration and velocity, of the automated storage and retrieval systems. Due to this, literature defines statistical mean cycle times for many systems. ([Rit03], p. 16; [FEM03], p. 6) The detailed motion sequences of each AS/RS type are described in chapter 2.3.2, 2.4.2 and 2.5.2 respectively.

2.2.4.4 Cycle criterion

The cycle criterion correlates to the inverse of the mean number of working cycles and defines the number of working cycle per time unit. ([Rit03], p. 16)

2.2.5 Dwell point policy

The dwell point[19] is defined as the position where the vehicle/crane resides when the system is in idle. A machine is said to be idle if it is fully functional but no assignment of storage or retrieval processes is done. In other words machine idleness takes place when a AS/RS completes a storage or retrieval task and there is no immediate next request due to a lack of tasks. Periods of activity and idleness are constantly changing thus every component of the machines experiences times where no task is assigned. As a conclusion it is of strategic advantage to pre-position the crane/vehicle due to anticipated storage or retrieval processes. Furthermore, some types of AS/RS like shuttle systems (see chapter 2.5) use the dwell point to charge its rechargeable battery pack or super capacitor.[20] ([BW84]) were the first to outline dwell point policies. ([RV08], p. 353) lists four simple static possibilities:

Table 2: Overview of static dwell-point rules for unit load AS/RS[21][22]

Rule	Dwell-point
Input station	• Travel to the input station following the completion of any cycle
Midpoint	• Travel to the midpoint location in the rack following the completion of any cycle
Input/output point	• Return to the input station following the completion of a SC storage command; remain at the output station following the completion of either a SC retrieval or DC cycle
Last location	• Remain at the storage location following the completion of a SC storage; remain at the output station following the completion of either a SC retrieval or a DC cycle

[19] Not to be confused with dwell time which is the time between storage and retrieval process of a unit load

[20] Table 2 is not directly applicable to shuttle systems. The dwell points of these systems are mainly hoisting platforms or dedicated parking positions within the rack

[21] ([RV08], p. 353)

[22] [VTV12], p. 181

2.2.6 Position of I/O point[23]

Another factor that influences the operation of AS/RS are the positions of the input and output points of unit loads. Along with the dwell-point strategy the position of the I/O point affects the expected travel time.

Table 3 lists the most general possibilities:

Table 3: General overview of I/O positions[24]

Location	Description
Single location	• Input and output at the same end and elevation of the rack (with or without elevation) • Input and output at the same elevation, but at a midpoint in the rack
Single I/O at various locations	• Many I/O points of type single location
Multiple locations	• Input and output at opposite ends of the rack, but at the same elevation • Input and output at the same end of the rack, but at different elevations • Input and output at the opposite ends of the rack and at different elevations

2.2.7 Request sequencing

While the exact point in time at which a unit load is stored in a storage compartment is not of much importance, a retrieval operation is linked with a due time that should be met somehow. Usually a storage request is therefore performed using the first-come-first-serve (FCFS) principle, but for retrievals one has to sequence the request in a smarter way. In addition, a clever sequencing strategy enables an overall improvement of the AS/RS throughput. ([VTV12], p. 193; [RV08], p. 353)

In other words the request sequencing rules determine the queuing discipline for the storage and retrieval request queues. ([LW87] cited in ; [VTV12], p. 193) The pairing of storage and retrieval requests in one dual command cycle is called “interleaving”. ([FM09], p. 153) Since the list of retrieval and storage tasks is continuously changing, ([HMS87]) suggested two ways of how to deal with this dynamic problem. The first approach is to select a “block” of the most urgent requests, sequence them and select the next block. This process is called “block sequencing”. The other possibility is to re-sequence the whole list of storage and retrieval request and sort them by introducing due times and priorities. This type is called “dynamic sequencing”. ([RV08], p. 353). Table 4 lists the various heuristics that were developed in order to overcome dynamic sequencing problems.

[23] The I/O point is also called the P&D station (pickup-and-delivery)

[24] (Based upon [BW84]; [RV08], p. 356)

Table 4: Algorithms and heuristics for dynamic request sequencing of unit load AS/RS[25]

Rule	Description
First-come-first-serve (FCFS)	Retrieval request will be scheduled in order of appearance
Total travel time (TT) **Shortest total travel (STT)**	Selects a pair of locations such that the sum of the travel time for storage, retrieval and the interleaving time (empty travel from storage to retrieval location) are minimum
On-line asymmetric traveling salesman problem (ATSP) **Chebyshev traveling salesman problem (CTSP)**	Approach includes heuristics and an optimal branch-and-bound method to determine sequences for all known loads
Shortest leg (SL)	Storage locations are selected such that the least extra distance needs to be travelled to perform the storage request while traveling to the retrieval location
Shortest completion time (SCT) **Shortest completion time without output priority (SCTop)** **Shortest completion time with controlled output priority (SCTcop)**	Retrieval request with shortest completion time will be served first Modified SCT rule, in which the retrieval requests have first priority, to clear the room for storage Modified SCT rule, in which the retrieval requests would have the first priority only when the retrieval queue is longer than the storage queue.
Nearest-neighbor (NN) **Dynamic nearest-neighbor (DNN)**	Pairs of storage and retrieval requests are chosen such that the distance from the storage to the retrieval location is minimum Modified NN rule, in which the whole retrieval queue is the block

2.2.8 Order batching/ order allocation

Order batching is mainly applied to man-on-board AS/RS, since the problem behind order batching is very similar to batching problems for order pickers in ordinary warehouses. None the less order allocation is also of interest for AS/RS with a load handling capacity which is greater than 1 and if the AS/RS is aisle-changing.

Basically order batching describes a control policy and methodology that is used to consider a way of how to combine a number of random orders that need to be retrieved in one single

[25] (Based upon [BW84]; [RV08], p. 356)

tour of the crane or AS/RS vehicle. If the number of orders to be retrieved is not large, it takes a considerably long time to pick each order individually, hence when orders are small there is the possibility to reduce travel times by picking a group of orders. Most order allocation algorithms include the following three steps:[26] [27]

- Seed selection rule
- Order addition rule
- Stopping rule

The initial process which selects the first order and assigns it to the first batch is called the seed selection rule. Based upon the order addition rule, other similar orders are assigned to the batch until the well-defined stopping rule decides if the order is already completed (see Figure 17). According to ([RV08], p. 351) a very important assumption that all heuristics have in common is the fact that a single order cannot be split over various batches, but needs to be picked as a whole. When considering order batching in the light of average travel times, the analysis done by ([Pan95]) have to be mentioned. The authors presented a study that compares four seed selection and four order addition rules regarding average travel time comparing the shape factor, capacity and the storage assignment policy. ([Pan95]) conclude that only the capacity of the crane/vehicle has an effect in the selection of order batching algorithms. ([VTV12], p. 199)

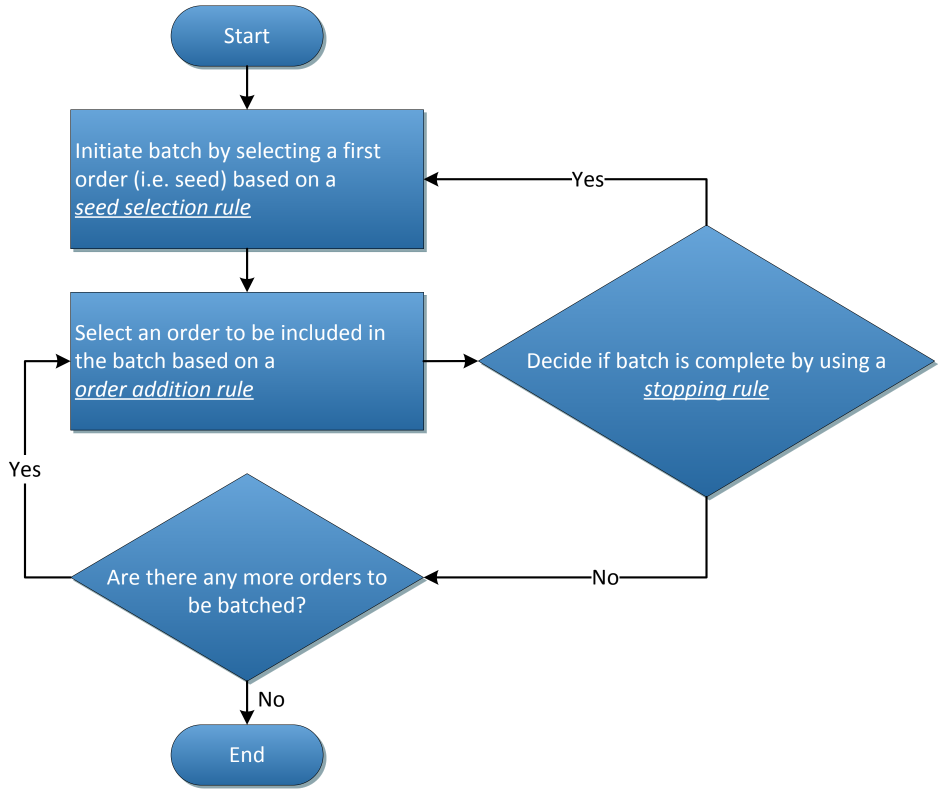

Figure 17: Common structure of order batching heuristics[28]

[26] ([VTV12], p. 197)
[27] ([RV08], p. 351)
[28] (Modified after [VTV12], p. 198 and ; [RV08], p. 352)

Table 5: Overview of seed selection, order addition and stopping rules for order batching[29]

Type of rule	Rule
Seed selection	• Order with largest number of locations to be visited • Order with smallest number of locations to be visited • Order with largest volume • Order with smallest volume • Order with highest percentage of capacity of crane • Cumulative rule • Clustering rule
Order addition	• Largest number of common locations • Geometric similarities
Stopping rules	• Capacity constraint • Time constraint • All orders are completed

2.2.9 Load shuffling/sorting heuristics

Since the time for storage and retrieval processes is vital to automated storage and retrieval systems, it can be advantageous that the already stored goods are rearranged or simply shuffled. (Pre-)Sorting and relocation is especially important for retrieval tasks. While for storage any empty storage compartment can be used, retrieval tasks are always designated to a single specific location. In order to minimized the response time for retrieval, unit loads that have a high demand frequency but are stored far away from the I/O point for any reason, can be relocated during off-peak or idle periods. ([VTV12], p. 201)

Load shuffling can also be applied to storage processes so that the storage travel time can be optimized. This means that the unit-load is stored into a random storage compartment that can be reached in the shortest time but is not the final storage destination. The unit-load gets rearranged to its assigned storage compartment while the AS/RS is in idle again. Sorting heuristics have another positive effect beside shortening travel times. Since idle times are used, the utilization degree of the AS/RS rises. Unfortunately very little information regarding load shuffling strategies can be found in literature. This might be because existing load shuffling strategies are applied during idleness, hence for systems with a low utilization degree. AS/RS with high utilization do not idle very often therefore it is doubtful that these strategies are useful in practice. ([VTV12], p. 201)

29 ([RV08], p. 352)

2.3 Rack feeder (stacker crane)

According to ([VDI93]), a rack feeder is a discontinuously working rack serving unit which moves horizontally and vertically within the aisles of a high-bay storage facility. The rack feeder, which is also referred to as stacker crane or simply storage and retrieval (S/R) machine, consists of several components. The bottom carriage contains a travel drive unit that rides along at least one travel rail.[30] In case the transshipping performance of the warehouse is very low, the rails can be constructed in a way, in which the rack feeder is able to change from one aisle to another, enabling a saving in costs. The travel drive unit is designed using a conventional friction or geared belt drive. A single or double mast, which is guided by another rail at the top, is furthermore mounted onto the travel drive unit. The mast is made out of steel, aluminum or carbon fiber to ensure a very rigid construction that is also lightweight by the way. It carries a hoist unit that holds a load handling device. The lifting carriage is driven by a geared belt, a chain or a rope. By means of the guidance provided by the rails, a rack feeder can simultaneously move along the x- and y-axis using its drive and hoist unit at the same time. The dimensioning of the drive units has to be made by taking the desired velocity and torque patterns into consideration ([Sch99], p. 34; [Arn08], p. 663)

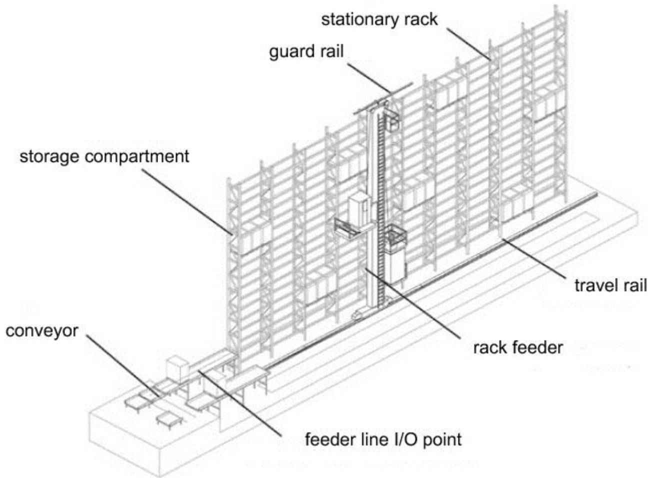

Figure 18: Pallet stacker crane in a high-bay warehouse[31]

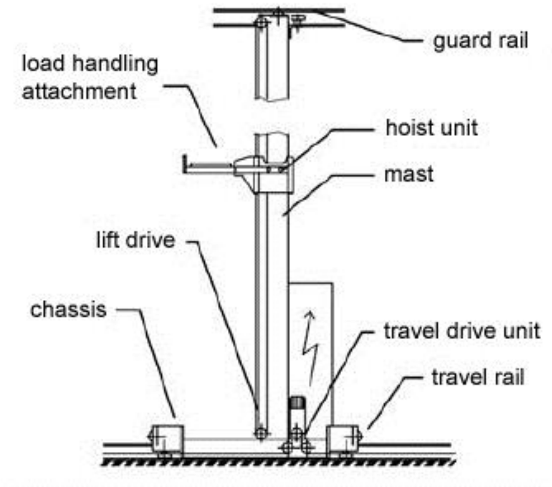

Figure 19: Components of a rack feeder[32]

The load handling device can be constructed in several different ways carrying loads ranging from small load carriers to complete palettes. Therefore the type and number of unit loads, that can be carried, strongly depends on which design is used. In general a telescopic fork,

[30] More rails are also possible
[31] ([tH11], p. 126)
[32] ([Arn08], p. 664)

as depicted in Figure 20, is used to handle the unit loads as it enables the feeding of a rack on both sides.[33]

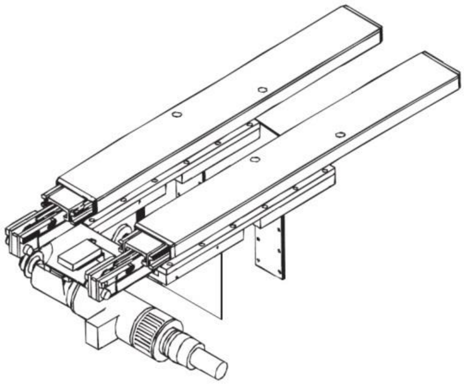

Figure 20: Telescopic fork load handling device[34]

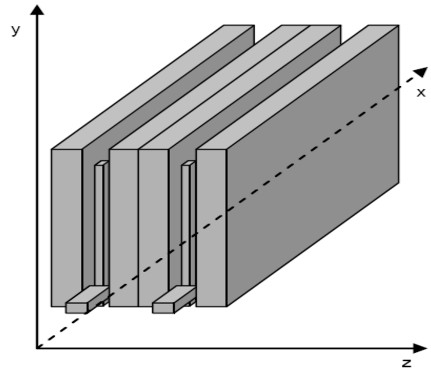

Figure 21: Coordinate system of stacker crane[35]

Types of rack framework construction

There are two opposed types of constructions that can be used when building a rack feeder. The hall type of construction is a warehouse were the racks of the AS/RS and the encasing hall are statically not connected to each other. This type is mainly used for high-bay storage facilities with a rack height of at least 12 m. In contrast the racks in a silo type of construction are the supporting structure where the outer shell is fixed. Since there is no individual building the racks have to absorb all external forces. ([tH11], p. 123)

Types of rack feeder

According to ([Gro08], p. 322) rack feeder can be classified into several important categories. Table 6 lists the most important types that are theoretically within the scope of this thesis.

Table 6: Excerpt of rack feeder types[36]

Principal type	Description
Unit load AS/RS	Typically a unit load rack feeder is a large automated storage and retrieval system to handle unit loads stored on pallets or other standardized containers. The system is designed to be fully automated and controlled by a computer. The term unit load rack feeder is the most generic description, all other types described below can be seen as variants
Deep-lane AS/RS	A deep-lane rack feeder is used in high-density warehouses, where large quantities of a comparably small number of separated SKUs are to be stored. Since

[33] (For further readings see [Arn08], p. 666)
[34] ([AF07], p. 201)
[35] ([Woh00], p. 6)
[36] ([Gro08], p. 322–324)

	it is of no necessity that each single unit load is directly accessible from the aisle, the deep-lane crane stores more loads in a single rack, one behind the next (please note: deep-lane storage is not to be confused with double-deep storage)
Miniload AS/RS	Miniload stacker cranes are solely used to handle small loads that are contained in a bin, a drawer or within a cardboard box. The S/R machine and its load handling device is designed to store and retrieve the bins fully automated. A human worker at the I/O point withdraws the needed items, whereupon the bin is returned to its location in the system. In general a miniload system is comparably smaller than an ordinary unit load stacker crane. Sometimes the rack is completely enclosed due to security reasons (theft).

2.3.1 Coordinate system

As can be seen in Figure 21, the rack feeder's travel drive unit moves horizontally along the x-axis at a speed of v_x, while the hoist unit elevates along the y-axis at a speed of v_y. The distinct characteristic of these two axis is, that both can be actuated simultaneously. If the movements are started synchronously, the load handling attachment travels along a linear path[37] that satisfies the equation:[38]

$$y = \frac{v_y}{v_x} * x \qquad \text{Equation 7}$$

Since in the majority of cases v_x, and v_y are not of the same order, the travel times are determined by the proportion of the different speeds in relation to the vertical and horizontal dimensions of the rack. Therefore the so called <u>shelf unit parameter</u> w is defined:[39]

$$w = \frac{\frac{h_{RM}}{l_{RM}}}{\frac{v_y}{v_x}} = \frac{v_x}{v_y} * \frac{h_{RM}}{l_{RM}} \qquad \text{Equation 8}$$

As can be seen in Figure 22, the diagonal along which $w = 1$ splits the rack into two areas. The first area contains all storage compartments that are critical regarding hoist time, whereas the second area is critical regarding travel time.

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[37] Scientific research projects already investigate in the pros/cons of non-linear travel paths

[38] ([AF07], p. 198)

[39] ([AF07], p. 199)

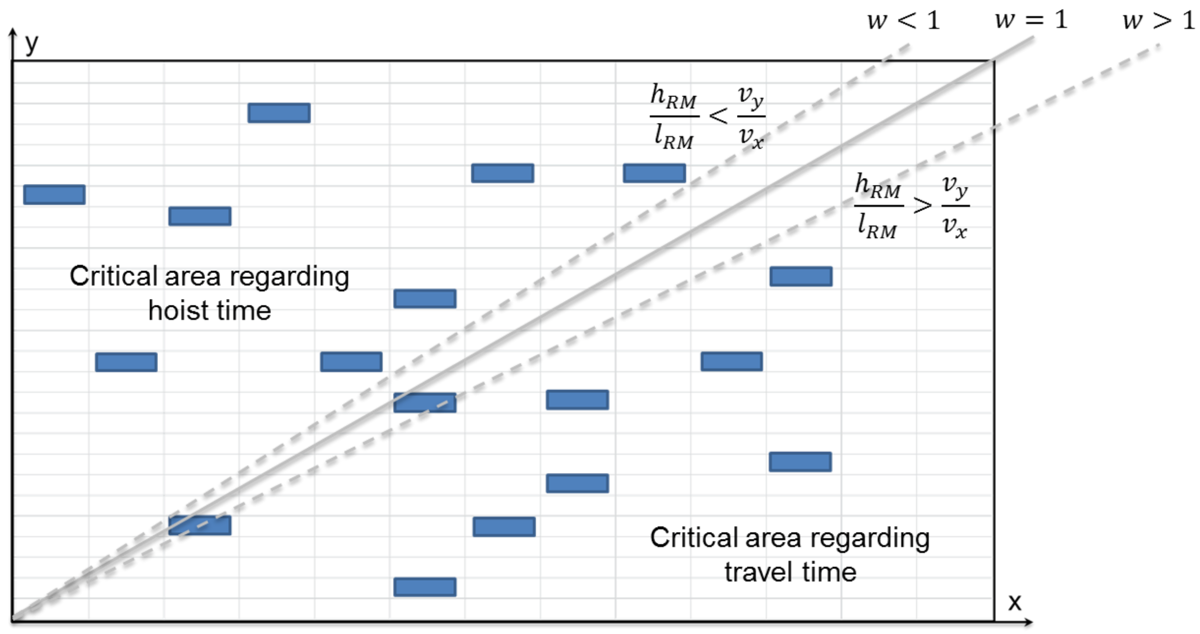


Figure 22: Shelf unit parameter w

This can be described easier when taking a look at two different storage/retrieval scenarios:

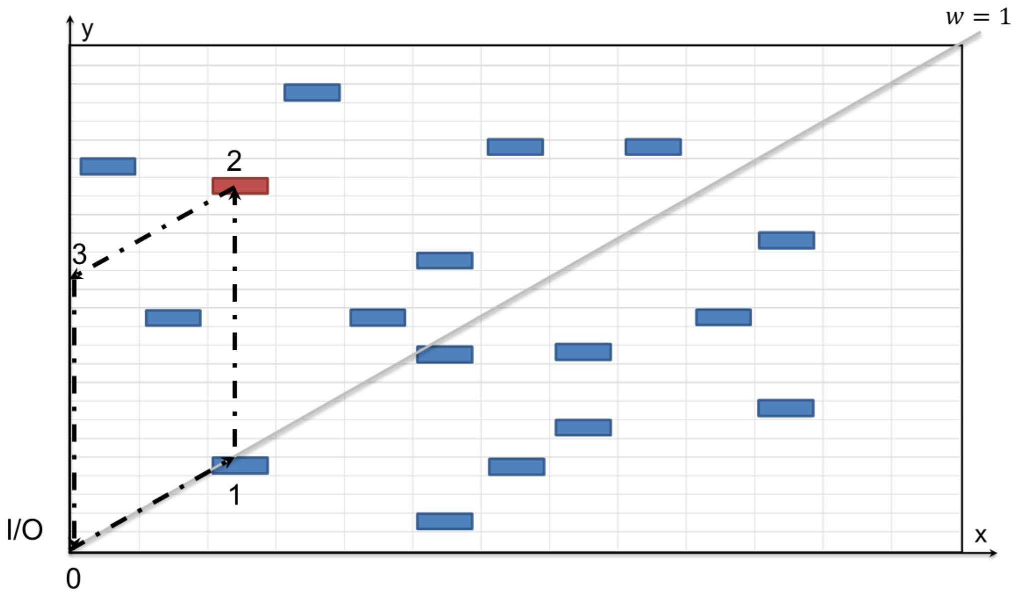


Figure 23: Storage compartment in critical area regarding hoist time[40]

The first scenario is depicted in Figure 23 and shows a single cycle storage process in the area critical regarding hoist time. One can easily see, that the drive unit can already be stopped at point 1. The distance between point 1 and 2 is only done by the hoist unit. The same is true when returning back to the I/O point. Consequently the cycle time of the hoist unit t_y predominates the total cycle time.

[40] (Cf.[AF07], p. 200)

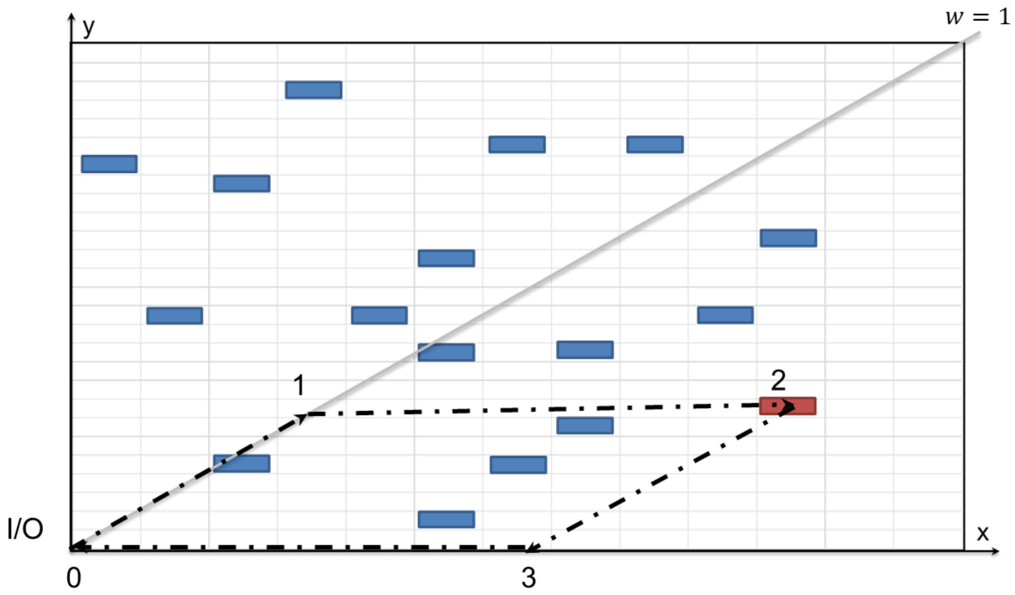


Figure 24: Storage compartment in critical area regarding travel time[41]

The second scenario is depicted in Figure 24 and shows a single cycle retrieval process in the area critical regarding travel time. One can easily see, that this time the hoist unit can already be stopped at point 1. The distance between point 1 and 2 is only done by the drive unit. The same is true when returning back to the I/O point. Consequently the cycle time of the drive unit t_x predominates the total cycle time. Having both scenarios in mind, one can recognize that the same values of t_x and t_y are not only true for the red-marked storage compartments but also for all others where $l_x = const.$ and $l_z = const.$ These lines are called Isochrones and represent storage position which have the same travel/hoist time as well as the same cycle times.

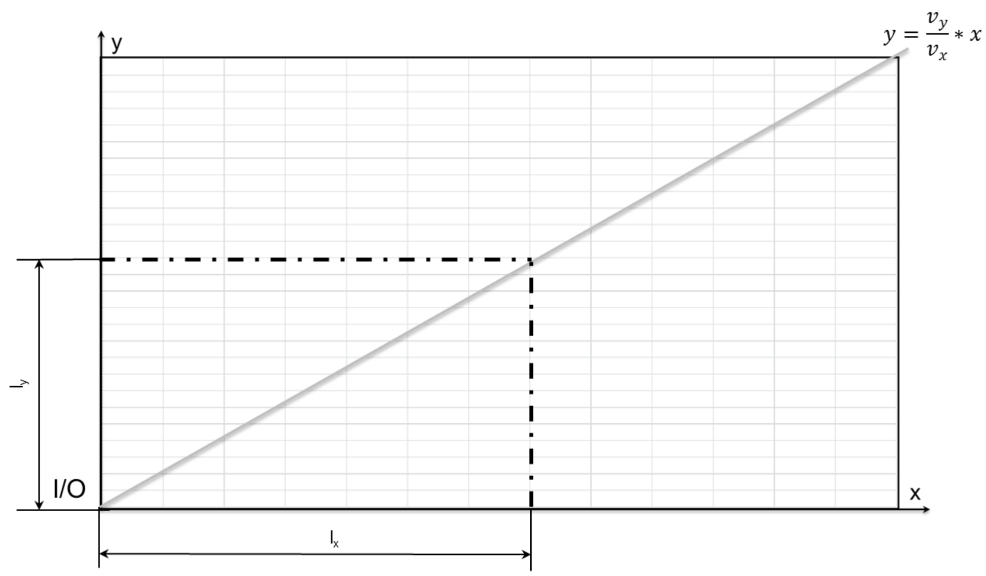


Figure 25: Isochrones where $t_x = t_z = const.$ for all storage compartments[42]

[41] (Cf.[AF07], p. 200)

Last but not least, the z-axis of a stacker crane relates to the direction that is used for storing and retrieving items from its storage compartments and travels at a speed of v_z.

2.3.2 Calculation of throughput

2.3.2.1 Working cycles of rack feeders

As already outlined in chapter 2.2.4, several different working cycles can be defined. This section is going to cover the detailed motion-sequence which is especially true for rack feeders. This sequences are the basis in order to calculate the throughput, thus to verify the logistical capabilities of a stacker crane. ([FEM03], p. 4) defines the following subroutines for single cycle (Figure 26) and for double cycle (Figure 27) storage and retrieval processes.

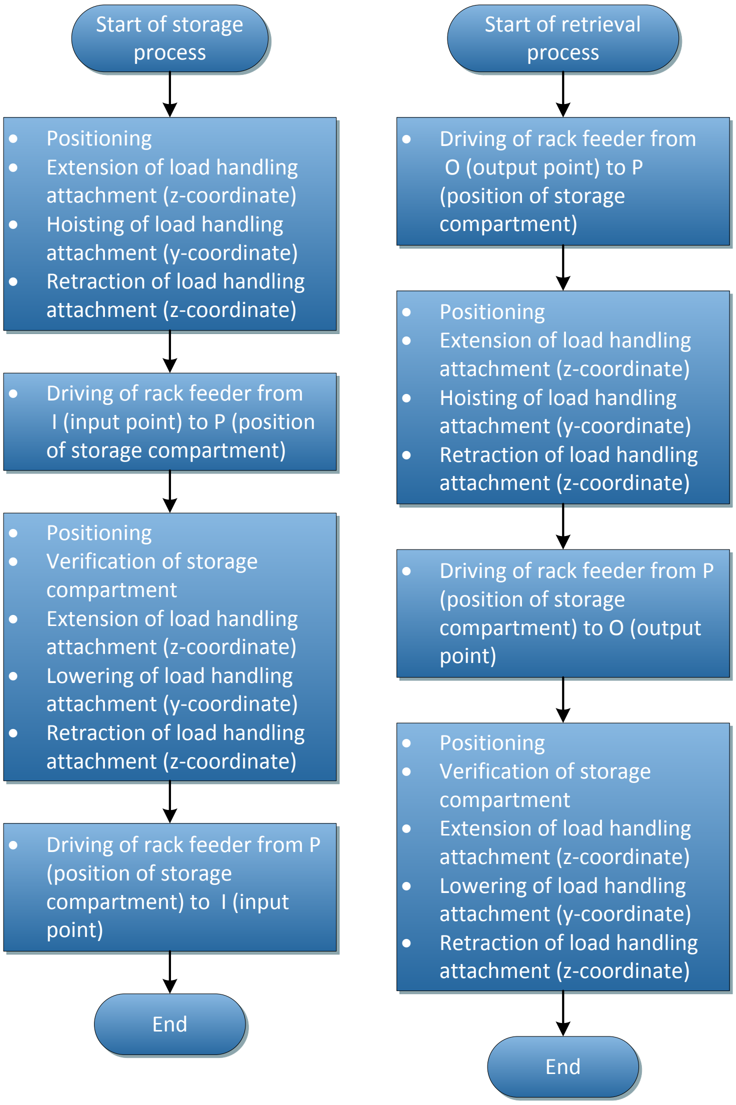


Figure 26: Motion-sequence for storage and retrieval process in a single cycle[43]

[42] (Cf.[AF07], p. 200)
[43] ([FEM03], p. 4)

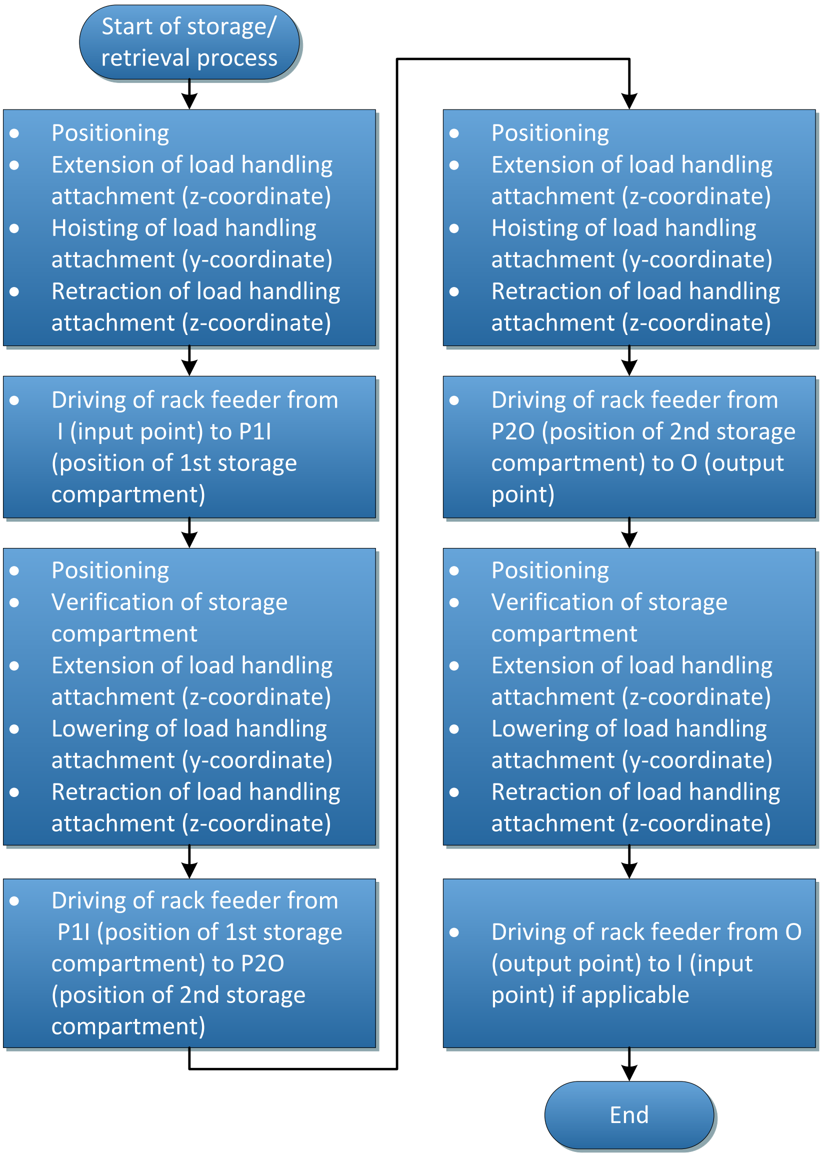


Figure 27: Motion-sequence for storage and retrieval process in a double cycle[44]

2.3.2.2 Derivation of mean cycle time and throughput calculation

The derivation of the equation for the mean cycle time and thus the throughput that is described in the following chapter can be found in ([See06], p. 66 ff.).

Mean cycle time for a single cycle

The cycle time consists of times for travelling in both x- and y- coordinate at the same time, times for picking or dropping of the load and downtime for verification tasks or other functions.

$$t_s = t_0 + 2 * t_z + 2 * \max[t_x; t_y] \quad \text{Equation 9}$$

[44] ([FEM03], p. 4)

The expected value for the cycle time t_s between the I/O point and any of the m storage compartments is:

$$E(t_s) = \sum_{i=1}^{m} t_{s_i} * p_i$$ Equation 10

$$p_i = \frac{1}{m} = const.$$ Equation 11

The downtime as well as the time needed by the load handling device can be considered to be constant, hence the expected value for the cycle time is essentially influenced by the track-dependent time. Therefore the expected value for this part accounts to:

$$E(t_l) = \sum_{i=1}^{m} \frac{t_{l_i}}{m}$$ Equation 12

Table 7: Nomenclature of cycle times for a single command

Nomenclature	
t_S	Cycle time for a single cycle
t_0	Downtime (positioning, etc.)
t_z	Cycle time for load handling device
$t_{i,j} = max[t_x, t_y]$	Max. value of both travel-dependend times (driving and hoisting)
p_i	Probability of approaching storage compartment i by S/R machine
m	Total amount of storage compartments

The times t_{l_i} result from the maximum time needed to travel in either x- or y-coordinate whichever is the greatest value. The exact motion sequence strongly depends on the equipment (eg. electric drive) and the programming by the manufacturer. A trapezoid velocity curve, which is depicted in Figure 28, is very common in order to compensate oscillations.

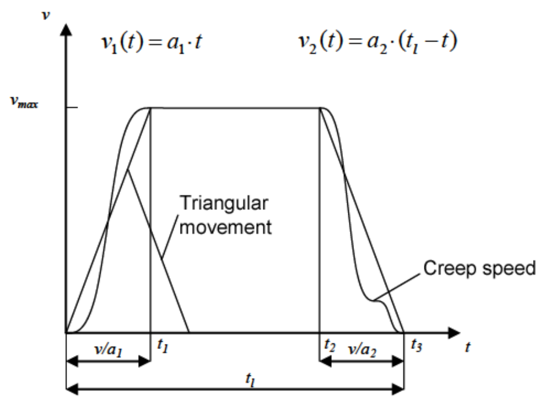


Figure 28: Real and simplified velocity curve of stacker crane[45]

[45] (Modified from [See06], p. 64)

$$t_{l_i} = \max[t_x; t_y] \quad \text{Equation 13}$$

For calculation the real velocity curve is linearized. If the acceleration and deceleration differ hugely, a mean acceleration is taken for even more simplification. If the nominal velocity is reached during the movement to or from a storage compartment, it is called trapeze driving.

$$a_1 = a_2 = a = \frac{2 * |a_1 * a_2|}{a1 + |a2|} \quad \text{Equation 14}$$

Trapezoid movement:

$$l \geq \frac{v^2}{a} \quad \text{Equation 15}$$

$$v = v_{max}; a = const. \quad \text{Equation 16}$$

$$l = \int_0^{t_l} v(t)dt = v * t_l - \frac{v^2}{a} \quad \text{Equation 17}$$

$$t_l = \frac{l}{v} + \frac{v}{a} \quad \text{Equation 18}$$

Due to the assumption of $v = v_{max}$ and $a = const.$, the acceleration and deceleration is a constant time interval, while the other term is a track-dependent part. If the nominal velocity is not reached during the movement to or from a storage compartment, it is called triangular driving.

Triangular movement:

$$l < \frac{v^2}{a} \quad \text{Equation 19}$$

$$v \neq v_{max} \quad \text{Equation 20}$$

$$l = a * t_l^2 \quad \text{Equation 21}$$

$$t_l = \sqrt{\frac{l}{a}} \quad \text{Equation 22}$$

The relative failure that arises when using Equation 16 for all cycle times, can be neglected when contrasting the little amount of triangular movements compared to the vast amount of working cycles. Therefore the expected value for the travel-dependent time is calculated by using the equation:

$$E(t_l) = \sum_{i=1}^{m} \frac{1}{m} * \max[\left(\frac{x}{v_x} + \frac{v_x}{a_x}\right); \left(\frac{y}{v_y} + \frac{v_y}{a_y}\right)] \quad \text{Equation 23}$$

Consequently the expected value can be calculated numerically by inserting all coordinates. But Equation 23 can also be used to find an analytical solution by considering it as infinitesimal.

$$m = \frac{F}{\Delta F} = \frac{F}{\Delta \mathrm{x} * \Delta \mathrm{y}} \quad \text{Equation 24}$$

$$F = L * H \quad \text{Equation 25}$$

$$\Delta F = \Delta x * \Delta y \quad \text{Equation 26}$$

Table 8: Nomenclature for infinitesimal consideration

Nomenclature	
L	Total length of rack
H	Total height of rack
F	Area of the rack

$$m \to \infty \quad \Delta x \to dx \quad \Delta y \to dy$$ Equation 27

$$E(t_l) = \frac{1}{L * H} \int_{y=0}^{H} \int_{x=0}^{L} \max\left[\left(\frac{x}{v_x} + \frac{v_x}{a_x}\right); \left(\frac{y}{v_y} + \frac{v_y}{a_y}\right)\right] dxdy$$ Equation 28

([Sch68]) solves the integral, substitutes the shelf unit parameter and states the following equations for the expected value of the half single cycle:

$$E(t_l) = \left(1 - \frac{w}{2}\right) * \frac{v_x}{a_x} + \frac{w}{2} * \frac{v_y}{a_y} + \frac{L}{v_x} * \left(\frac{1}{2} + \frac{1}{6} * w^2\right) \qquad w \leq 1$$ Equation 29

$$E(t_l) = \frac{1}{2 * w} * \frac{v_x}{a_x} + \left(1 - \frac{1}{2 * w}\right) * \frac{v_y}{a_y} + \frac{L}{v_x} * \left(\frac{w}{2} + \frac{1}{6w}\right) \qquad w \geq 1$$ Equation 30

$$E(t_l) = \frac{1}{2} * \left(\frac{v_x}{a_x} + \frac{v_y}{a_y}\right) + \frac{2}{3} * \frac{L}{v_x} \qquad w = 1$$ Equation 31

When comparing Equation 32 with Equation 18 one can see that the amount of time needed for acceleration and deceleration $t_{\bar{a}}$ is not track-dependent and therefore can be considered as constant.

$$\frac{L}{v_x} = \frac{H}{v_y}$$ Equation 32

$$t_{\bar{a}} = \frac{1}{2} * \left(\frac{v_x}{a_x} + \frac{v_y}{a_y}\right)$$ Equation 33

Hence the track-dependent parts lead to the equation:

$$\frac{2}{3} * \frac{L}{v_x} = \frac{x}{v_x}$$ Equation 34

$$x = \frac{2}{3} * L$$ Equation 35

And if $w = 1$ (Equation 8), then the following is true:

$$\frac{2}{3} * \frac{L}{v_x} = \frac{2}{3} * \frac{H}{v_y} = \frac{y}{v_y}$$ Equation 36

$$y = \frac{2}{3} * H$$ Equation 37

All storage compartments on these coordinates take the same time $t_x = t_y$, since they are located on isochrones. Inserted in Equation 9, the mean cycle time for a single cycle for all storage compartments accounts to:

$$E(t_s) = t_0 + 2 * t_z + 2 * \mathrm{E}(\mathrm{t_l})$$ Equation 38

$$E(t_s) = t_0 + 2 * t_z + \left(\frac{v_x}{a_x} + \frac{v_y}{a_y}\right) + \frac{4}{3} * \frac{L}{v_x}$$ Equation 39

Mean cycle time for a double cycle

The same correlations can also be derived for dual command cycles. The cycle time consists again of times for travelling in both x- and y- coordinate at the same time, times for picking or dropping of the load and downtime for verification tasks or other functions.

$$t_s = t_0 + 4 * t_z + t_{IP} + t_{PP'} + t_{P'O}$$ Equation 40

Table 9: Nomenclature of cycle times for a double command

Nomenclature	
t_S	Cycle time for a double cycle
t_0	Downtime (positioning, etc.)
t_z	Cycle time for load handling device
t_{IP}	Max. time for distance from I/O point to first storage locations
$t_{PP'}$	Max. time for distance from first to second storage location
$t_{P'O}$	Max. time for distance from second storage location to I/O point
$p_{i,j}$	Probability of approaching storage compartment i, j by S/R machine
m	Total amount of storage compartments

The expected value for the total mean cycle time is therefore:

$$E(t_s) = t_0 + 4 * t_z + E(t_{IP}) + E(t_{PP'}) + E(t_{P'O})$$ Equation 41

With P and P' being two random storage compartments in the rack (for P with $i = 1, 2 \ldots m$ and P' with $j = 1, 2 \ldots m$, whereas $i \neq j$), the expected value for storage and retrieval can be calculated using Equation 12:

$$E(t_{IP}) = \sum_{i=1}^{m} \frac{t_{l_i}}{m}$$ Equation 42

$$E(t_{P'O}) = \sum_{i=1}^{m} \frac{t_{l_j}}{m}$$ Equation 43

Equation 41 and Equation 42 can be solved according to Equation 31, which leads to the situation that only the expected value for the travel time from the first to the second storage compartment is to be derived. Under the assumption that all containers are evenly distributed, the probability of all storage compartments to be approached by the miniload is:

$$p_{i,j} = \frac{1}{m * (m - 1)}$$ Equation 44

As a result the expected value can be found according to Equation 23:

$$E(t_{PP'}) = E(t_l)_{i,j} = \sum_{i=1}^{m}\sum_{j=1}^{m} t_{l_{i,j}} * p_{i,j} = \frac{1}{m*(m-1)} * \sum_{i=1}^{m}\sum_{j=1}^{m} \max[(t_{x,x'});(t_{y,y'})]$$ Equation 45

The travel times between point P and P' correlate to Equation 18:

$$t_{x,x'} = \frac{|x-x'|}{v_x} + \frac{v_x}{a_x}$$ Equation 46

$$t_{y,y'} = \frac{|y-y'|}{v_y} + \frac{v_y}{a_y}$$ Equation 47

Transferring the discrete model into a continuous one leads to:

$$m \to \infty \quad \Delta x \to dx \quad \Delta x' \to dx' \quad \Delta y \to dy \quad \Delta y' \to dy'$$ Equation 48

$$E(t_l)_{i,j} = \frac{1}{(L*H)^2}\int_0^H\int_0^H\int_0^L\int_0^L \max\left[\left(\frac{|x-x'|}{v_x}+\frac{v_x}{a_x}\right);\left(\frac{|y-y'|}{v_y}+\frac{v_y}{a_y}\right)\right] dxdx'dydy'$$ Equation 49

Considering the special case $w = 1$, then the integral for the travel time can be solved again according to ([Sch68]):

$$E(t_l)_{i,j} = \frac{1}{2} * \left(\frac{v_x}{a_x}+\frac{v_y}{a_y}\right) + \frac{14}{30} * \frac{L}{v_x} \qquad w = 1$$ Equation 50

Equation 41, Equation 42 and Equation 50 together result in the expected values for the total mean cycle time:

$$E(t_s) = t_0 + 4 * t_z + \frac{3}{2} * \left(\frac{v_x}{a_x}+\frac{v_y}{a_y}\right) * \frac{4}{3} * \frac{L}{v_x} + \frac{14}{30} * \frac{L}{v_x}$$ Equation 51

All storage compartments on the coordinates of Equation 35 and Equation 37 take the same time $t_x = t_y$ again, since they are located on isochrones as well. Further the equation can be geometrically interpreted, which leads to the two reference points P and P' which are separated by the following distances:

$$|x-x'| = \frac{14}{30} * L$$ Equation 52

$$|y-y'| = \frac{14}{30} * L$$ Equation 53

This interrelationship is also depicted in Figure 57.

2.3.2.3 Mean cycle time and throughput according to FEM 9.851

The “Fédération européenne de la manutention” (FEM) has published the engineering standard FEM 9.851 called “Leistungsnachweis für Regalbediengeräte – Spielzeiten” that defines cycle times for fully automatic storage and retrieval systems with a stacker crane. The standard defines six different system layouts and describes a consistent methodology to calculate the cycle times as well as the throughput according to the methodology that was shown in the previous chapter. It can be used for optimization and is applicable to all phases of usage ranging from planning to launching the complete system. ([FEM03])

Since the exact calculation and analysis for each system are very complex, FEM 9.851 acts on the assumption that the usage of all storage compartments is uniformly distributed (cf.

chapter 2.2.3.2) if the time interval is long enough. Hence the cycle time for single or dual command cycles are based on this statistical average value. Due to the comparably low effort needed to determine the mean cycle times and the relatively good convergence to the exact cycle times, ([FEM03]) has demonstrated a good performance in practice. The area of application depends on the shelf unit parameter. In order to get significant results, the shelf unit parameter is limited to $0{,}5 < w < 2$. If $w \neq 1$ the cycle time differs from the theoretically calculated values. In Table 10 - Table 15 the different use cases of FEM 9.851 are presented:

Use cases of FEM 9.851

Table 10: FEM 9.851 use case 1

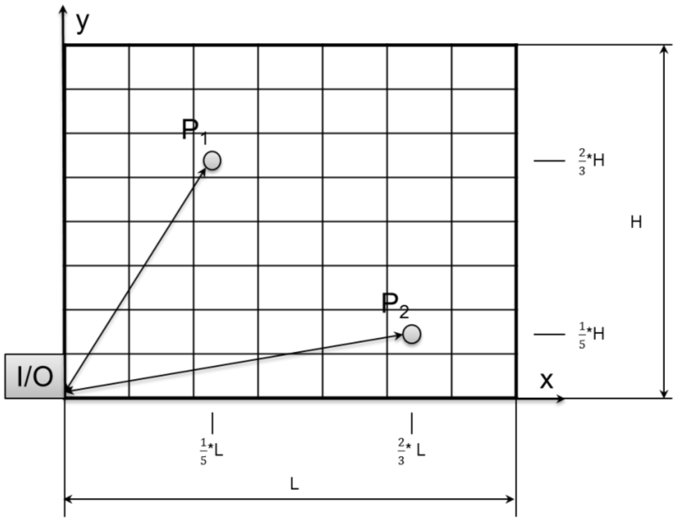
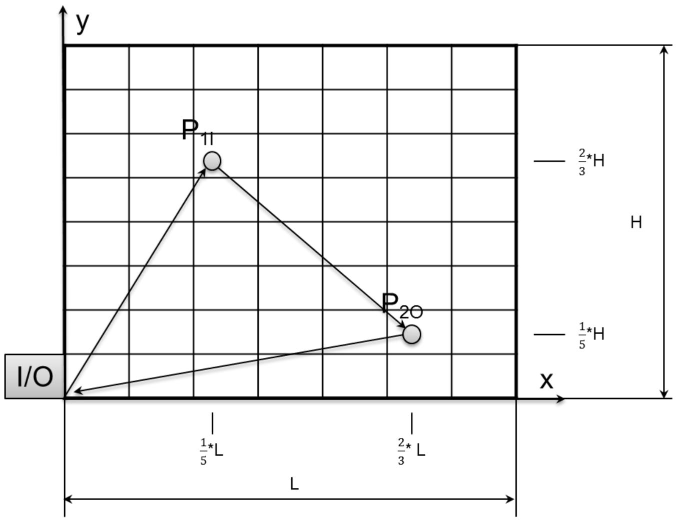
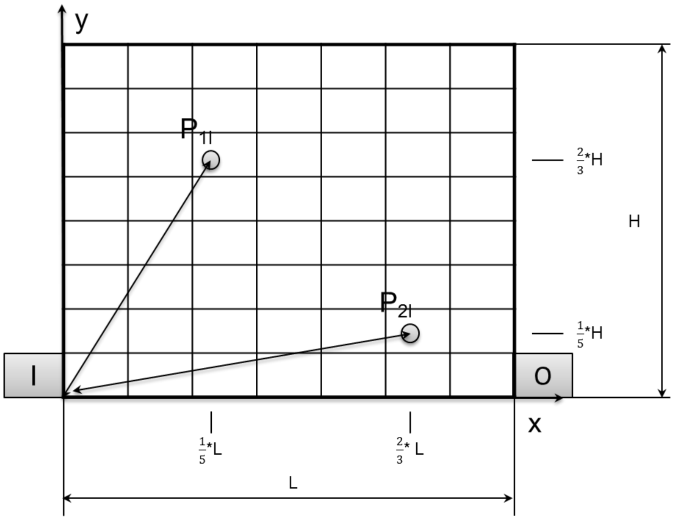
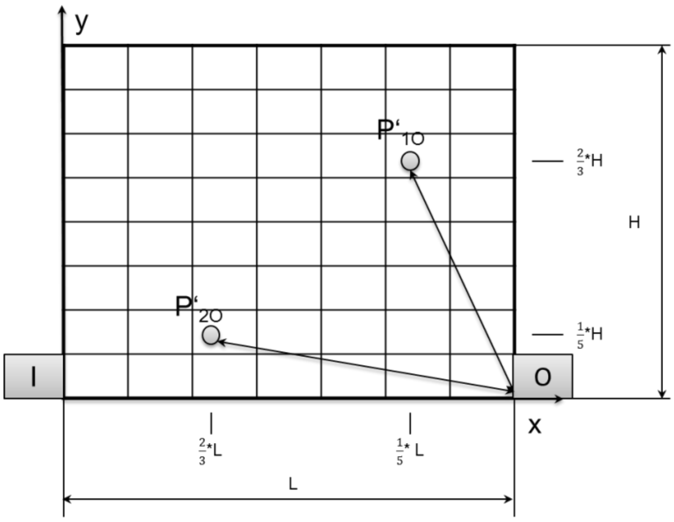
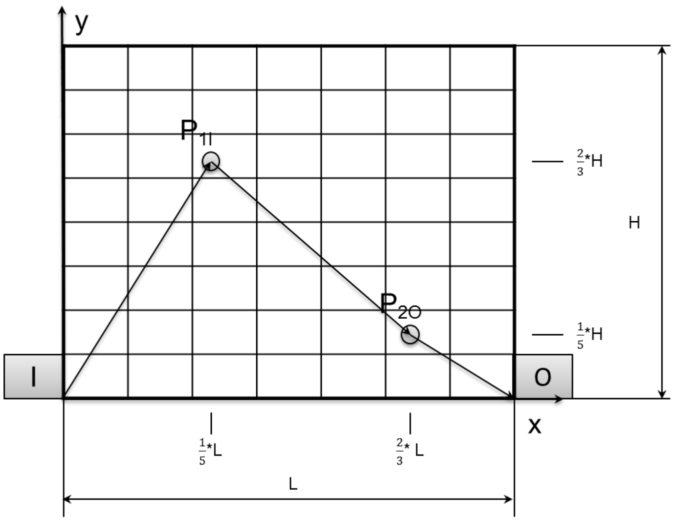
<table>
<tr><th>Input and output point at the same end and elevation of the rack</th><th colspan="2">Process type & cycle time</th></tr>
<tr><td rowspan="2">
</td><td colspan="2">SC storage & retrieval cycle:
$t_{m1} = \frac{1}{2} * (t_{P1} + t_{P2}) + t_{01}$</td></tr>
<tr><td>$I = \binom{0}{0}$
$O = \binom{0}{0}$</td><td>$P_1 = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$
$P_2 = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$</td></tr>
<tr><td rowspan="2">
</td><td colspan="2">DC storage &retrieval cycle:
$t_{m2} = t_{P1I}, t_{P2O} + t_{02}$</td></tr>
<tr><td>$I = \binom{0}{0}$
$O = \binom{0}{0}$</td><td>$P_{1I} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$
$P_{2O} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$</td></tr>
</table>

Table 11: FEM 9.851 use case 2

Input and output point at opposite ends of the rack but at same elevation	Process type & cycle time	
 	SC storage cycle: $t_{m1} = \frac{1}{2} * (t_{P1I} + t_{P2I}) + t_{01}$	
	$I = \binom{0}{0}$ $O = \binom{0}{L}$	$P_{1I} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$ $P_{2I} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$
 	SC retrieval cycle: $t_{m1} = \frac{1}{2} * (t_{P'1O} + t_{P'2O}) + t_{01}$	
	$I = \binom{0}{0}$ $O = \binom{0}{L}$	$P'_{1O} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$ $P'_{2O} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$
 	DC storage & retrieval cycle: $t_{m2} = \frac{1}{2} * \big(t_{P1I;P2O;O;I} + t_{P'1I;P'2O;O;I}\big) + t_{02}$	
	$I = \binom{0}{0}$ $O = \binom{0}{L}$	$P_{1O} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$ $P_{2O} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$

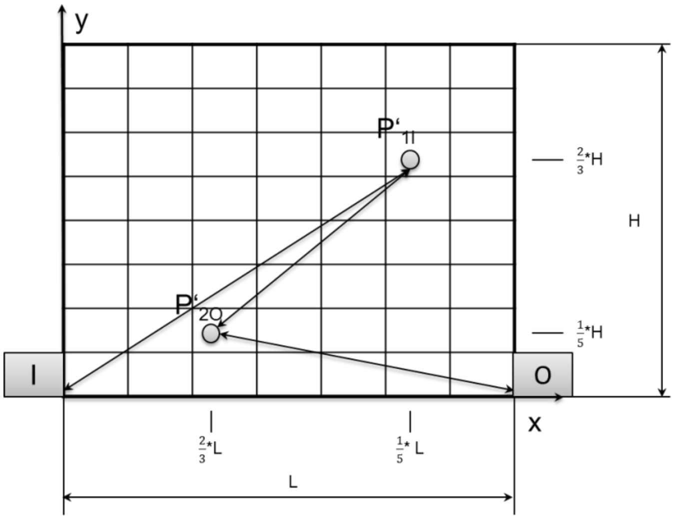
<table>
<tr>
<td>
</td>
<td>$I = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$
$O = \begin{pmatrix} 0 \\ L \end{pmatrix}$</td>
<td>$P'_{1I} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$
$P'_{2O} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$</td>
</tr>
</table>

Table 12: FEM 9.851 use case 3

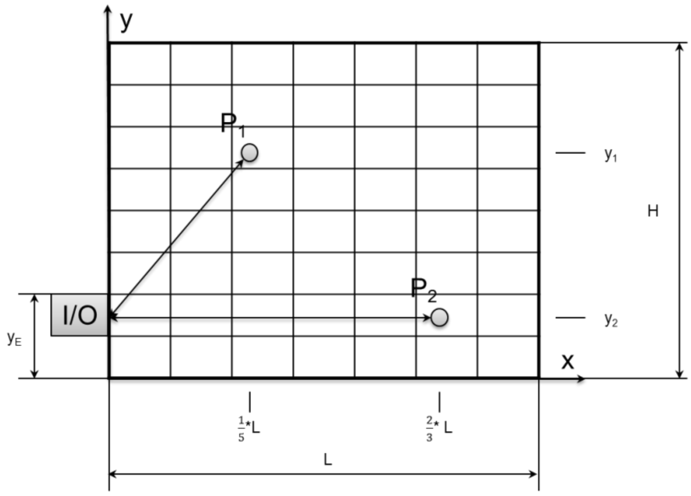
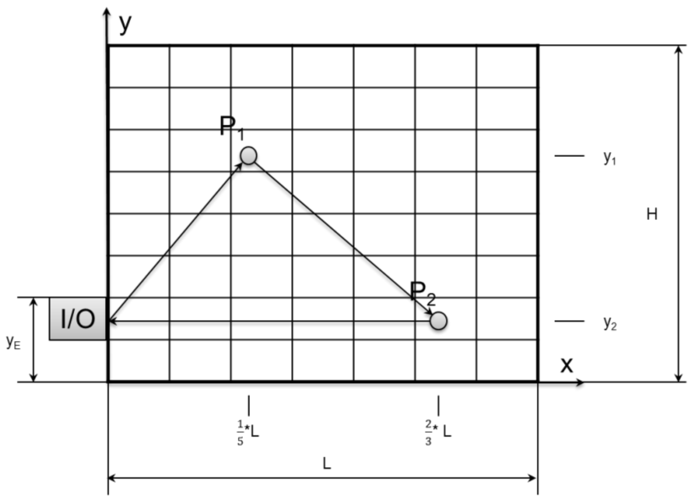
<table>
<tr>
<th>Input and output point at same end but elevated</th>
<th colspan="2">Process type & cycle time</th>
</tr>
<tr>
<td rowspan="3">
</td>
<td colspan="2">SC storage & retrieval cycle:
$t_{m1} = \frac{1}{2} * (t_{P1} + t_{P2}) + t_{01}$</td>
</tr>
<tr>
<td>$0 < y_E \leq \frac{H}{2}$</td>
<td>$\frac{H}{2} < y_E \leq H$</td>
</tr>
<tr>
<td>$IO = \begin{pmatrix} 0 \\ y_E \end{pmatrix}$
$P_1 = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H + \frac{1}{3}y_E \end{pmatrix}$
$P_2 = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H + \frac{1}{3}y_E \end{pmatrix}$</td>
<td>$IO = \begin{pmatrix} 0 \\ y_E \end{pmatrix}$
$P_1 = \begin{pmatrix} \frac{1}{5}L \\ \frac{1}{3}y_E \end{pmatrix}$
$P_2 = \begin{pmatrix} \frac{2}{3}L \\ \frac{7}{5}H + \frac{1}{3}y_E \end{pmatrix}$</td>
</tr>
<tr>
<td rowspan="2">
</td>
<td colspan="2">DC storage & retrieval cycle:
$t_{m2} = t_{P1I}, t_{P2O} + t_{02}$</td>
</tr>
<tr>
<td colspan="2">Same coordinates</td>
</tr>
</table>

Table 13: FEM 9.851 use case 4

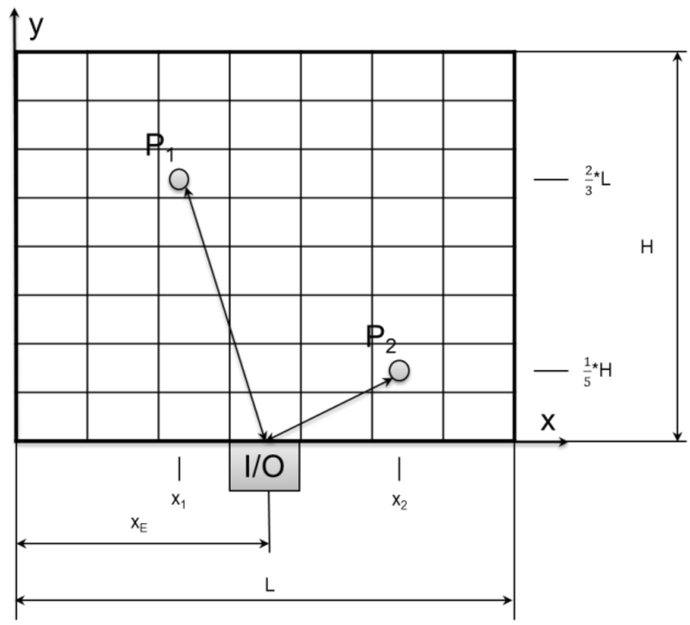
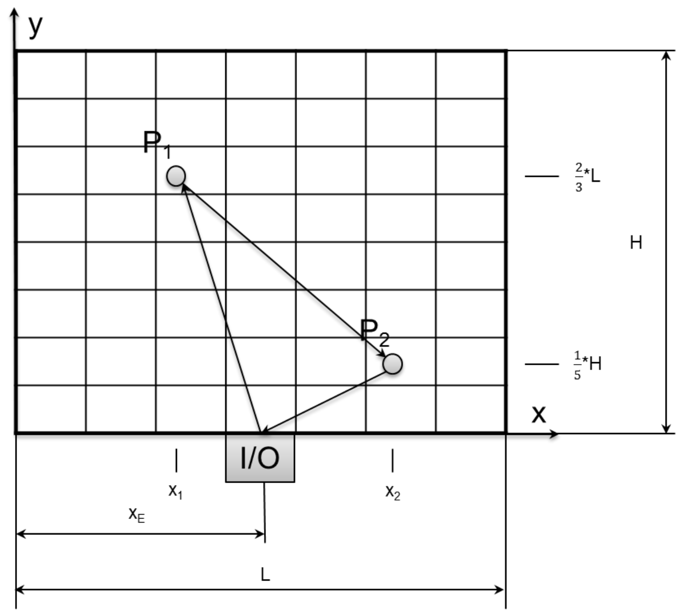
Input and output point at the same elevation, but horizontally shifted (not necessarily but possibly midpoint)	Process type & cycle time	
	SC storage & retrieval cycle: $t_{m1} = \frac{1}{2} * (t_{P1} + t_{P2}) + t_{01}$	
	$0 < x_E \leq \frac{L}{2}$	$\frac{L}{2} < x_E \leq L$
	$IO = \binom{x_E}{0}$ $P_1 = \begin{pmatrix} \frac{1}{5}L + \frac{1}{3}x_E \\ \frac{2}{3}H \end{pmatrix}$ $P_2 = \begin{pmatrix} \frac{2}{3}L + \frac{1}{3}x_E \\ \frac{1}{5}H \end{pmatrix}$	$IO = \binom{x_E}{0}$ $P_1 = \begin{pmatrix} \frac{7}{15}L + \frac{1}{3}x_E \\ \frac{2}{3}H \end{pmatrix}$ $P_2 = \begin{pmatrix} \frac{1}{3} * x_E \\ \frac{1}{5}H \end{pmatrix}$
	DC storage & retrieval cycle: $t_{m2} = t_{P1I}, t_{P2O} + t_{02}$	
	Same coordinates	

Table 14: FEM 9.851 use case 5

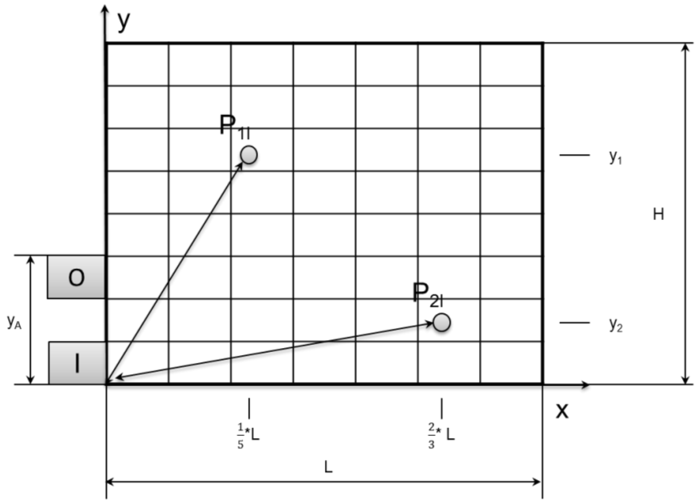
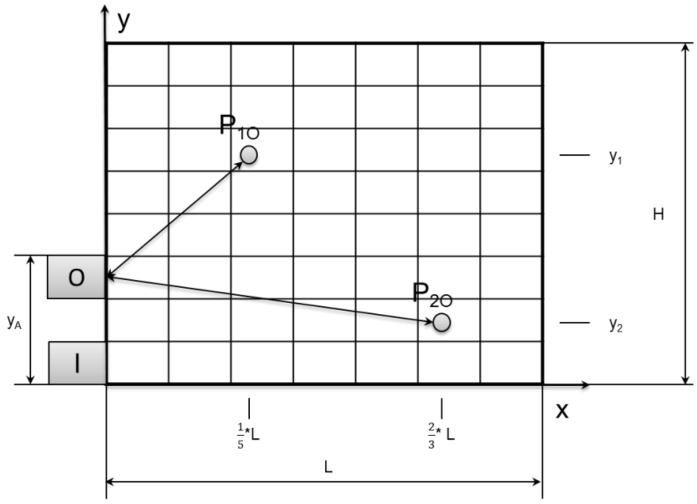
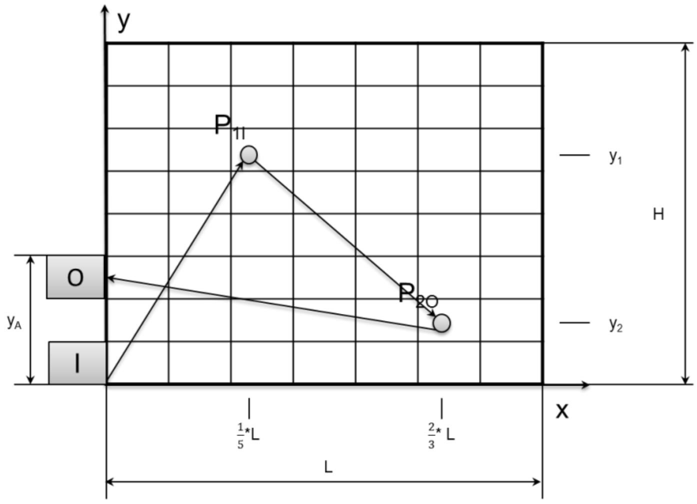
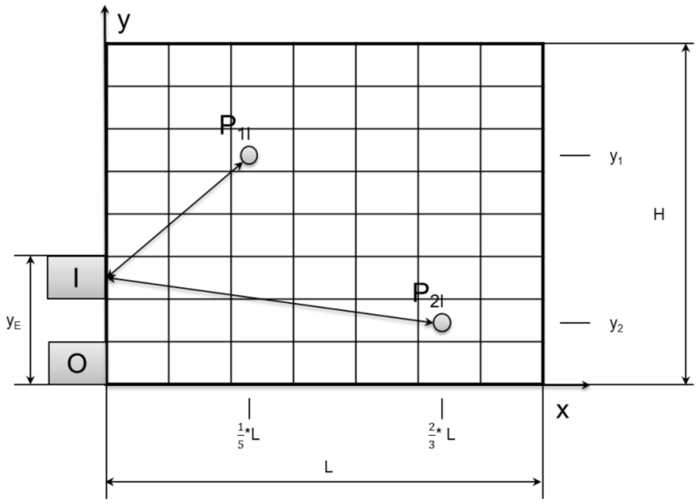
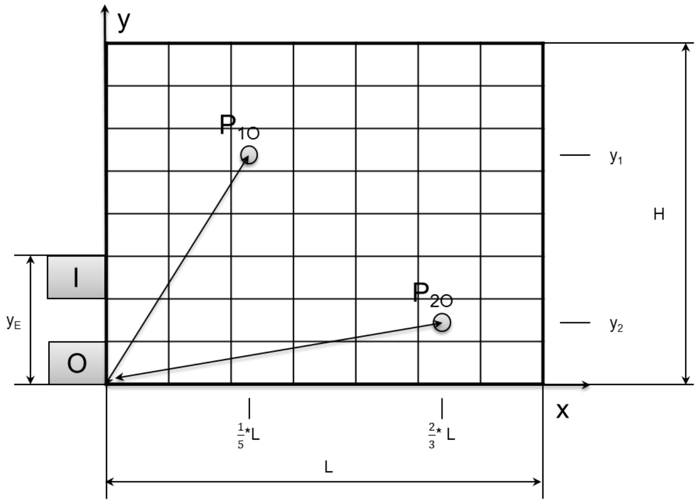
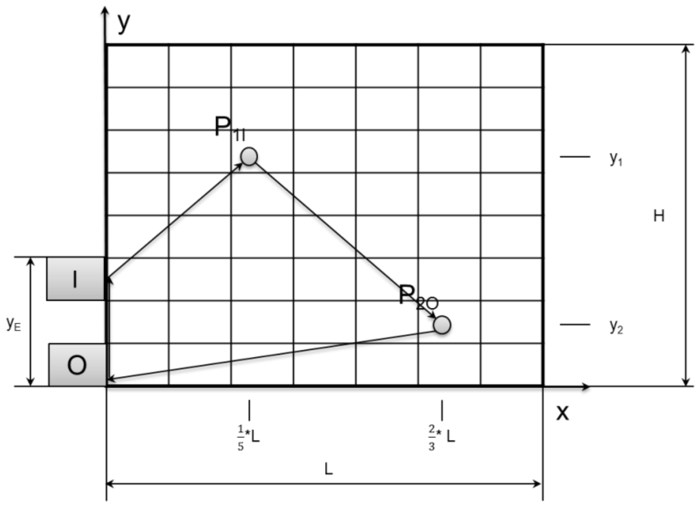
<table>
<tr><th>Input and output point at same end of the rack but with different elevations (output above input)</th><th colspan="2">Process type & cycle time</th></tr>
<tr><td rowspan="2">
</td><td colspan="2">SC storage cycle:
$$t_{m1} = \frac{1}{2} * (t_{P1I} + t_{P2I}) + t_{01}$$</td></tr>
<tr><td>$I = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$
$O = \begin{pmatrix} 0 \\ y_A \end{pmatrix}$</td><td>$P_{1I} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H + \frac{1}{3}y_A \end{pmatrix}$
$P_{2I} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H + \frac{1}{6}y_A \end{pmatrix}$</td></tr>
<tr><td rowspan="2">
</td><td colspan="2">SC retrieval cycle:
$$t_{m1} = \frac{1}{2} * (t_{P1O} + t_{P2O}) + t_{01}$$</td></tr>
<tr><td>$I = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$
$O = \begin{pmatrix} 0 \\ y_A \end{pmatrix}$</td><td>$P_{1O} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H + \frac{1}{3}y_A \end{pmatrix}$
$P_{2O} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H + \frac{1}{6}y_A \end{pmatrix}$</td></tr>
<tr><td rowspan="2">
</td><td colspan="2">DC storage & retrieval cycle:
$$t_{m2} = t_{P1I;P2O;O;I} + t_{02}$$</td></tr>
<tr><td>$I = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$
$O = \begin{pmatrix} 0 \\ y_A \end{pmatrix}$</td><td>$P_{1I} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H + \frac{1}{3}y_A \end{pmatrix}$
$P_{2O} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H + \frac{1}{6}y_A \end{pmatrix}$</td></tr>
</table>

Table 15: FEM 9.851 use case 6

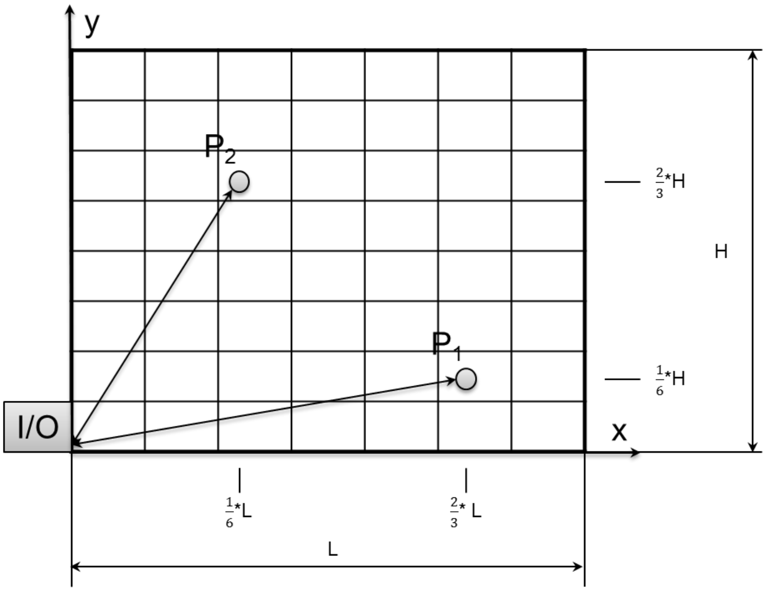
Input and output point at same end of the rack but with different elevations (input above output)	Process type & cycle time	
	SC storage cycle: $t_{m1} = \frac{1}{2} * (t_{P1I} + t_{P2I}) + t_{01}$	
	$I = \begin{pmatrix}0\\0\end{pmatrix}$ $O = \begin{pmatrix}0\\y_E\end{pmatrix}$	$P_{1I} = \begin{pmatrix}\frac{1}{5}L\\ \frac{2}{3}H + \frac{1}{3}y_E\end{pmatrix}$ $P_{2I} = \begin{pmatrix}\frac{2}{3}L\\ \frac{1}{5}H + \frac{1}{6}y_E\end{pmatrix}$
	SC retrieval cycle: $t_{m1} = \frac{1}{2} * (t_{P1O} + t_{P2O}) + t_{01}$	
	$I = \begin{pmatrix}0\\0\end{pmatrix}$ $O = \begin{pmatrix}0\\y_E\end{pmatrix}$	$P_{1O} = \begin{pmatrix}\frac{1}{5}L\\ \frac{2}{3}H + \frac{1}{3}y_E\end{pmatrix}$ $P_{2O} = \begin{pmatrix}\frac{2}{3}L\\ \frac{1}{5}H + \frac{1}{6}y_E\end{pmatrix}$
	DC storage & retrieval cycle: $t_{m2} = t_{P1I;P2I;O;I} + t_{02}$	
	$I = \begin{pmatrix}0\\0\end{pmatrix}$ $O = \begin{pmatrix}0\\y_E\end{pmatrix}$	$P_{1I} = \begin{pmatrix}\frac{1}{5}L\\ \frac{2}{3}H + \frac{1}{3}y_E\end{pmatrix}$ $P_{2O} = \begin{pmatrix}\frac{2}{3}L\\ \frac{1}{5}H + \frac{1}{6}y_E\end{pmatrix}$

Each theoretical testing point is of course assigned to a real storage compartment, that is next to the testing point P1 or P2.

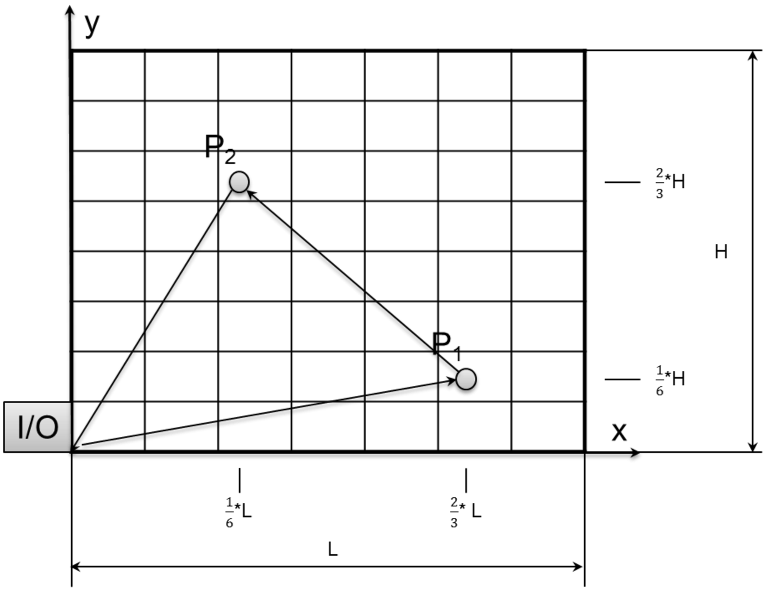
2.3.2.4 Mean cycle time and throughput according to VDI 3561/1-2

In 1973, the “Verein Deutscher Ingenieure” (VDI) published the guideline VDI 3561 called “Testspiele zum Leistungsvergleich und zur Abnahme von Regalförderzeugen”. Although the content of ([VDI73]) is not exactly the same as can be found in FEM 9.851, there are some similarities. Again the basic assumption is that the storage compartments are used uniformly. Within the testing procedure single and dual command cycles are conducted that represent the mean cycle time. The area of application also depends on the shelf unit parameter. In order to get significant results, the shelf unit parameter is limited to $0{,}5 < w < 2$. In Table 16 and Table 17 the calculation scheme of VDI 3561 is shown:

Table 16: Mean cycle time and throughput VDI 3561 – normal I/O point

<table>
<tr><th>Input and output point at the same end and elevation of the rack</th><th colspan="2">Process type & cycle time</th></tr>
<tr><td rowspan="2">


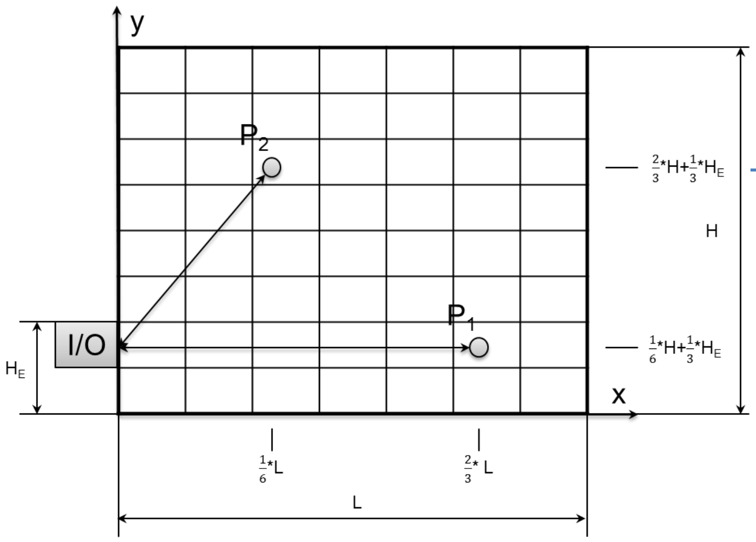
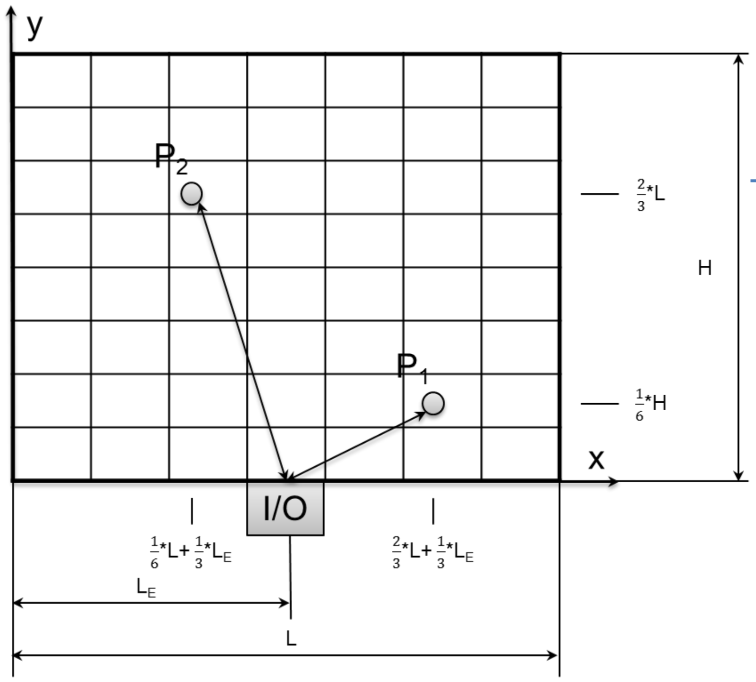
</td><td colspan="2">SC cycle:

$$t_{\bar{1}} = \frac{1}{2} * (t_1(P1) + t_2(P2))$$</td></tr>
<tr><td>$$I = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$ $$O = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$</td><td>$$P_1 = \begin{pmatrix} \frac{2}{3} L \\ \frac{1}{6} H \end{pmatrix}$$ $$P_2 = \begin{pmatrix} \frac{1}{6} L \\ \frac{2}{3} H \end{pmatrix}$$</td></tr>
<tr><td rowspan="2">


</td><td colspan="2">DC cycle:

$$t_{\bar{2}} = (t(P1P2))$$</td></tr>
<tr><td>$$I = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$ $$O = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$</td><td>$$P_1 = \begin{pmatrix} \frac{2}{3} L \\ \frac{1}{6} H \end{pmatrix}$$ $$P_2 = \begin{pmatrix} \frac{1}{6} L \\ \frac{2}{3} H \end{pmatrix}$$</td></tr>
</table>

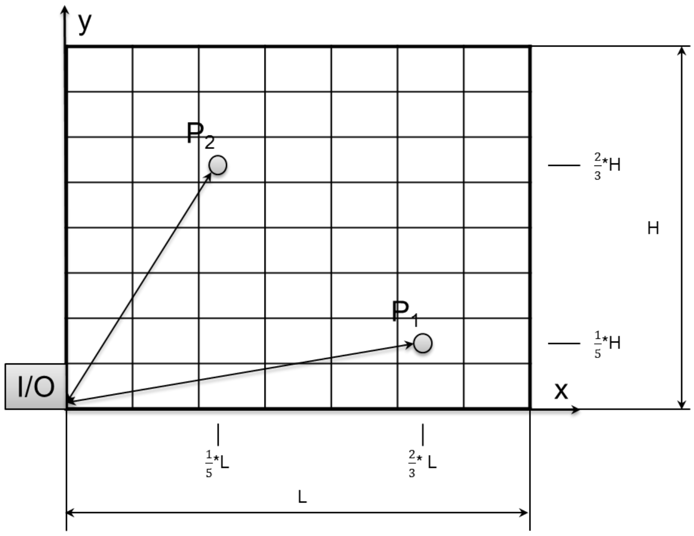
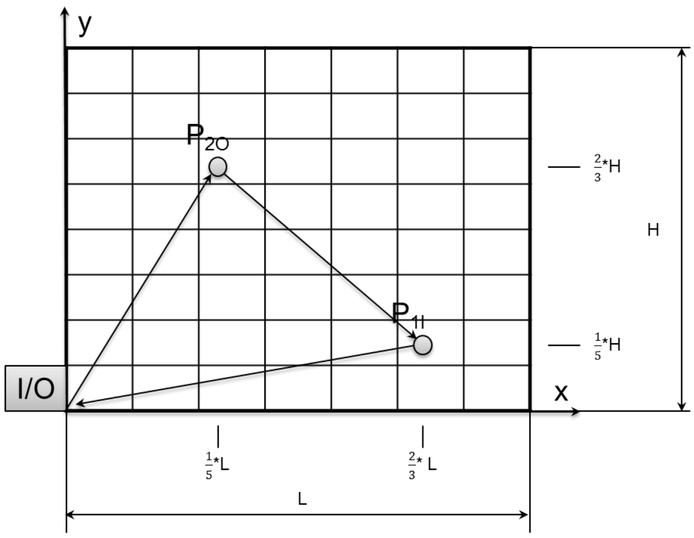
Table 17: Mean cycle time and throughput VDI 3561 – elevated or shifted I/O point

Input and output point at the same end but elevated or shifted	Type & cycle time
	Deviation in y-axis $t_{\overline{1}} = \frac{1}{2} * (t_1(P1) + t_2(P2))$ $I = \begin{pmatrix} 0 \\ H_E \end{pmatrix}$ $O = \begin{pmatrix} 0 \\ H_E \end{pmatrix}$ $P_1 = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{6}H + \frac{1}{3}H_E \end{pmatrix}$ $P_2 = \begin{pmatrix} \frac{1}{6}L \\ \frac{2}{3}H \end{pmatrix}$
	Deviation in x-axis $t_{\overline{2}} = (t(P1P2))$ $I = \begin{pmatrix} L_E \\ 0 \end{pmatrix}$ $O = \begin{pmatrix} L_E \\ 0 \end{pmatrix}$ $P_1 = \begin{pmatrix} \frac{2}{3}L + \frac{1}{3}L_E \\ \frac{1}{6}H \end{pmatrix}$ $P_2 = \begin{pmatrix} \frac{1}{6}L + \frac{1}{3}L_E \\ \frac{2}{3}H \end{pmatrix}$

2.3.2.5 Mean cycle time and throughput according to Gudehus

Another approach was developed by Gudehus in 1973. The suggested reference point are very similar to those in FEM 9.851, especially use case number one, which is identical. Again the basic assumption is that the storage compartments are used uniformly. Within the testing procedure single and dual command cycles are conducted in order to quantify the mean cycle time. In Table 18 the calculation scheme of Gudehus is depicted:

Table 18: Mean cycle time and throughput defined by Gudehus

Input and output point at the same end and elevation of the rack	Process type & cycle time	
	SC storage & retrieval cycle:	
	$I = \binom{0}{0}$ $O = \binom{0}{0}$	$P_1 = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$ $P_2 = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$
$\tau_E = \tau_A = 2 * t_0 + 2 * t_{xy}\begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix} + 2 * t_{xy}\begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix} + 2 * f_{LA} * t_z(B)$		
	DC storage &retrieval cycle: $t_{m2} = t_{P1I}, t_{P2O} + t_{02}$	
	$I = \binom{0}{0}$ $O = \binom{0}{0}$	$P_{1I} = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$ $P_{2O} = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$
$\tau_{EA} = 3 * t_0 + t_{xy}\begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix} + t_{xy}\begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix} + t_{xy}\begin{pmatrix} \frac{14}{30}L \\ \frac{14}{30}H \end{pmatrix} + 2 * f_{LA} * t_z(B)$		

2.4 Horizontal Carousel System/ Rotary rack

As described in chapter 2.2.1.2, carousel systems can be subsumed as dynamic warehouses with a relatively high throughput. The area of application differs widely but in general carousel systems are used for small to medium sized unit loads in manufacturing application due to their relatively low cost, versatility and reliability ([HH91], p. 1; [Gro08], p. 328) Depending on the orientation of circulation, two different types of carousel systems can be identified: ([Arn08], p. 655)

- Horizontal carousel systems: the driven conveyor chain or pulley is mounted within a horizontal plane, hence the storage fields are suspended like gondolas
- Paternoster warehouse: the driven conveyor chain and the affixed shelves move vertically[46]

Horizontal carousel systems can be sub-dived further into two groups:

- Single horizontal carousel systems (standard)
- Rotary Racks: a combination of a single horizontal carousel and a paternoster

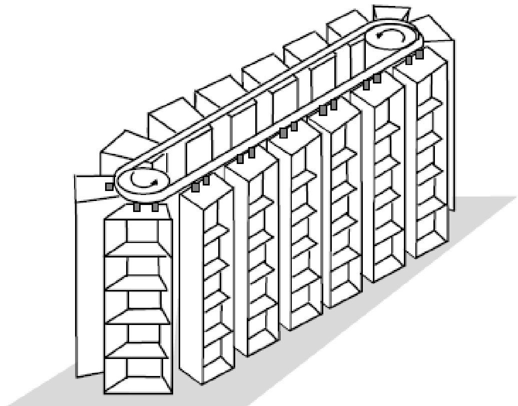


Figure 29: Single (standard) horizontal carousel[47]

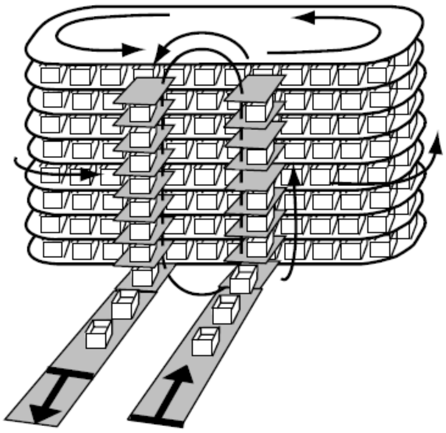


Figure 30: Rotary rack[48]

Figure 29 shows a standard horizontal carousel. It consists of a steel framework containing all storage fields that are moved synchronously and a storage and retrieval machine (see Figure 31) that resides stationary at the face-side of the rack. In contrast to that, a rotary rack, which is depicted in Figure 30, is able to move each single level independently, because it is composed of multiple horizontal carousel systems having either a special mechanical construction with a single drive-unit or a own drive-unit for each level. ([HKK99], p. 474; [Su98], p. 477) The rotation of the carousel can be both clock- or counter-clockwise. Systems with only unidirectional movement do exist but today's systems are generally bi-

[46] Due to their size and function (storage of small load carriers only) Paternoster warehouses are not further taken into consideration within this thesis

[47] ([Arn08], p. 656)

[48] ([Arn08], p. 656)

directional. ([Su98], p. 477) In order to prevent distortion of the frame, a carousel is equipped with at least two electric drives in each curve.

Horizontal carousel systems differ dramatically from all other considered AS/RS in two aspects. Due to the motion of the rack, the position of each storage compartment relative to the I/O point changes constantly from cycle to cycle. Furthermore the storage and retrieval machine and the carousel are able to move completely independent from each other, meaning while a pickup or retrieval operation is performed by the S/R robot, the carousel can rotate to the position of the next desired storage compartment at the same time. ([HH91], p. 12) Table 19 lists some basic differences between a basic rack feeder and a basic horizontal carousel system.

Figure 31: Double shuttle S/R machine for standard horizontal carousel system[49]

Table 19: Differences between a basic rack feeder and a carousel storage system[50]

Feature	Basic rack feeder	Basic horizontal carousel system
Storage structure	Rack system to support pallets or shelf system to support tote bins	Baskets/storage fields, suspended from overhead conveyor or trolleys
Motions	Linear motion of the S/R machine (stacker crane)	Revolution of overhead conveyor or trolleys around oval track
Storage/retrieval operation	S/R machine travels to storage compartment in rack structure	Conveyor revolves to bring baskets to load/unload (I/O) station
Replication of storage capacity	Multiple aisles, each consisting of a rack and a S/R machine	Multiple carousels, each consisting of oval track and suspended bins

[49] Source: SSI Schaefer-PEEM GmbH, Graz
[50] ([Gro08], p. 323)

According to ([Gud10], p. 603; [GK12], p. 467) the main advantages of Horizontal Carousel Systems can be described as the following:

- Compact storage system
- Better space utilization due to omission of aisles

Since this storage system is built very compact, each bin location is not easily accessible in case of a system malfunction. In general, access times can also be considered as quite long if the desired load unit is stored in a bin location on the other end of the rack. ([Gud10], p. 603) Therefore, in practice horizontal carousel systems are often combined to a cluster or pod consisting of several individual carousels, so that the picking process can be done simultaneously. This increases the work balance in a way, that no bottleneck is created and protects the operation in case of a system malfunction. In addition this necessitates that a product is to be stored in every carousel. ([BH11], p. 196) The best strategy to stock unit loads in a horizontal carousel system is to concentrate the most popular items in a so-called “organ pipe” arrangement (cf. chapter 2.2.3.5 Class-based storage assignment strategy). ([BH11], p. 197)

2.4.1 Coordinate system

Figure 32 shows the coordinate system that is used by horizontal carousel systems. The x-axis represents the length of the carousel, whereas the y- and z-axis are served by the storage and retrieval machine.

Figure 32: Coordinate system of horizontal carousel system[51]

[51] Source: SSI Schaefer-PEEM GmbH, Graz

2.4.2 Calculation of throughput

An analytical estimation of the performance of a horizontal carousel is quite difficult. Some theoretical approaches can be found in ([HKK99]), ([HH91]) and ([Su98]). A more practical approach is presented in the next chapter.

2.4.2.1 Mean cycle time and throughput according to VDI 4480-3

The series of guidelines VDI 4480 describes methodologies on how to calculate throughput for AS/RS. The conventions that can be found in VDI 4480 are universally valid for a variety of different systems and technologies and are independent of warehouse proportions, compared to other guidelines or standards. Part 3 of VDI 4480 called "Durchsatz von automatischen Umlauflager" applies to automated carousel storage systems.

In order to provide standard conditions for all systems, a uniform material flow is assumed. Dynamic influence or application-specific parameters like order structure or storage strategies are not taken into account (random storage assignment). The procedures assume that the technology is used under optimal conditions, hence no movement sequences or the like are prescribed. ([VDI99], p. 2)

For verifying the throughput several reference systems are defined. These system are based upon a standard coordinate system, the number and position(s) of the input and output points, points of origin and last but not least the effective reference storage locations. Each input and output point is allocated a fixed group of reference locations, which represent its own reference system. In every carousel storage system the total number of reference storage locations for each I/O point is the maximum value n, m, k of storage compartments in each coordinate x, y and z. The point of origin P_U is defined as being the nearest storage compartment from the input or output point, respectively. The first reference point R_1 is derived from P_U as follows:

- The x-coordinate of P_U is simultaneously the x-coordinate of R_1
- If the y-coordinate of P_U is equal to 1, then the y-coordinate of R_1 is equal to m
- If the y-coordinate of P_U is > 1, then the y-coordinate of R_1 is less than the y-coordinate of P_U by 1
- The z-coordinate of P_U is always equal to 1, the z-coordinate of R_1 is thus always equal to k

All further reference points can now be found by preceding from R_1, increasing the x-coordinate by 1 and decreasing the y-coordinate by 1. If $x = n$ and/or $y = 1$, the process starts again at $x = 1$ or $y = m$, until there is at least one reference storage location in every storage level or storage column. ([VDI99], p. 3, 12-13)

The throughput for input, output or a combined cycle is then measured by counting the unit loads at the I/O points and taking the time such that all incoming bins are stored and all outgoing bins are retrieved. The reference storage locations and I/O points can be approached in any sequence, but the whole cycle must be completely finished. ([VDI99], p. 24) Figure 33 shows an example of a horizontal carousel system and it's reference points.

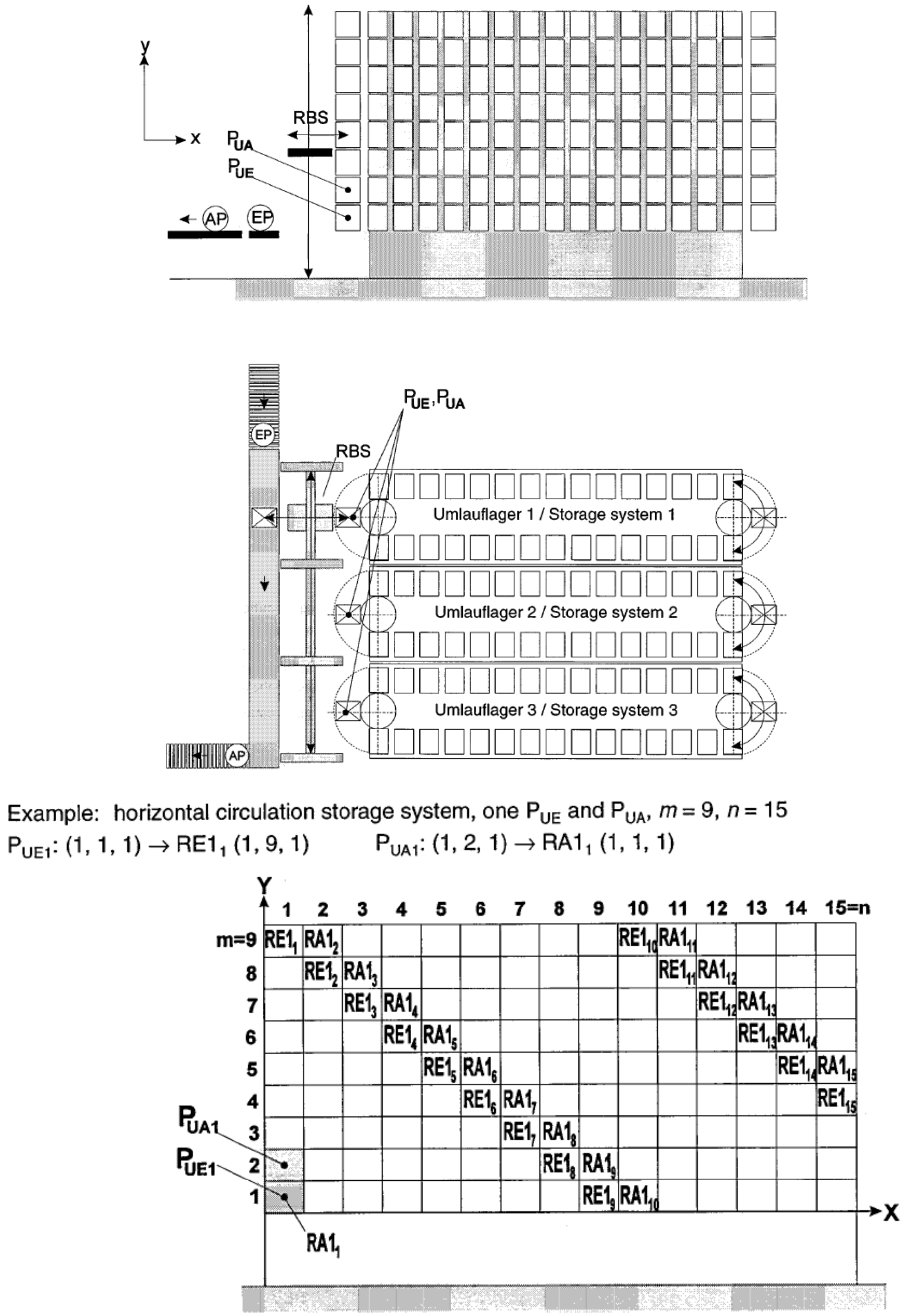


Figure 33: Example of a horizontal carousel system and it’s reference points[52]

[52] ([VDI99])

2.5 Shuttle System

The term shuttle system describes a small parts storage that is capable of storing and in some cases also externally transporting bins, trays or cardboard boxes. Together with the other storage solutions described in this master's thesis, shuttle systems are built to serve the "goods-to-man" principle. The fundamental distinctive feature of this storage system is the kind of movement when compared to other storage techniques with a static rack. Shuttle systems have the horizontal and vertical movement separated and carried out by two different components of the system. Vertical tasks are performed by a lift or an equivalent hoisting device, while horizontal movements are performed by small vehicles that are called shuttles (vehicles). Shuttle systems are a comparably new technology and have experienced a rapid development within intralogistics in recent years. Particularly the demands for more flexibility and higher throughput in high-bay warehouses as well as the fact that these systems are easily scalable have led to this development. That is also the reason why shuttle systems do exist in a great variety, especially regarding vehicle-, energy-, drive concepts and area of applications.

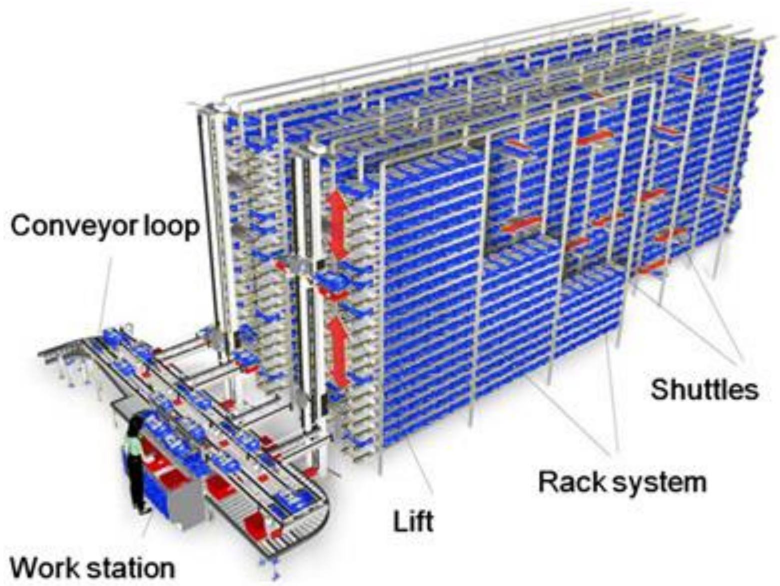


Figure 34: A typical Shuttle System[53]

The shuttle vehicle moves autonomously on top of longitudinal and/or transversal traverse members of the rack system. It is not possible for the vehicles to move without rolling along these rails since there is no floor plate within the aisles. In order to be able to retrieve important small load carriers in case of a system malfunction, service grids are installed in regular intervals. The ordinary storage process begins at the I/O point(s) where the lift fetches and transports the unit load into the desired storage level. A buffer zone is used to hand over the unit loads from the lifting device to the shuttle, which moves horizontally to the

[53] Cf. http://www.bastiansolutions.com/images/knapp-osr-shuttle/knapp-osr-shuttle_system.jpg?sfvrsn=4

corresponding storage compartment and unloads the bin. The retrieval process is done vice versa.

Typically, a vehicle is assigned to one single level of the rack but a few systems do exist that have less than one vehicle per shelf level. This is especially true for systems with intermediate throughput. Hence one has to distinguish between shuttle systems that are equipped with a container hoisting device or a vehicle hoisting device. Special lift platforms allow the shuttle to change between the different levels.

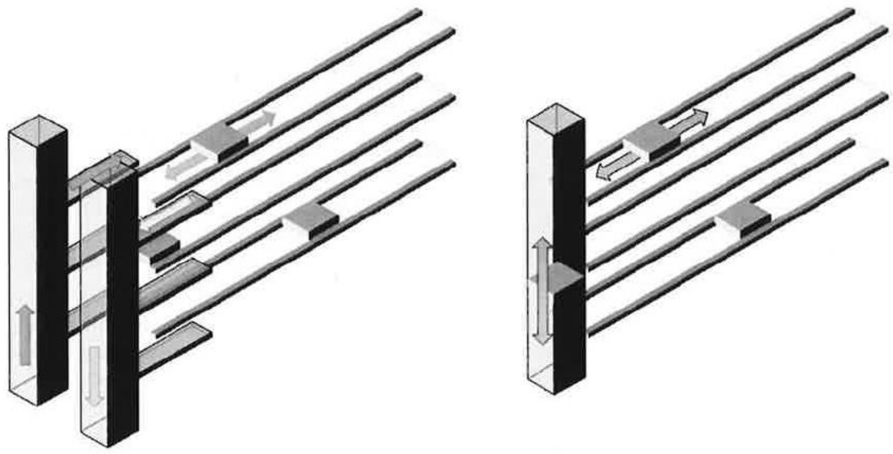


Figure 35: Basic concepts of shuttle systems: container lift (left) and vehicle lift (right)[54]

2.5.1 Coordinate system

Figure 36 shows the coordinate system that is used by shuttle systems. The shuttle vehicle moves along the x-axis, while the load handling device, which is attached to it, serves the z-axis. The hoisting unit or lift transports the unit loads or complete vehicle along the y-axis.

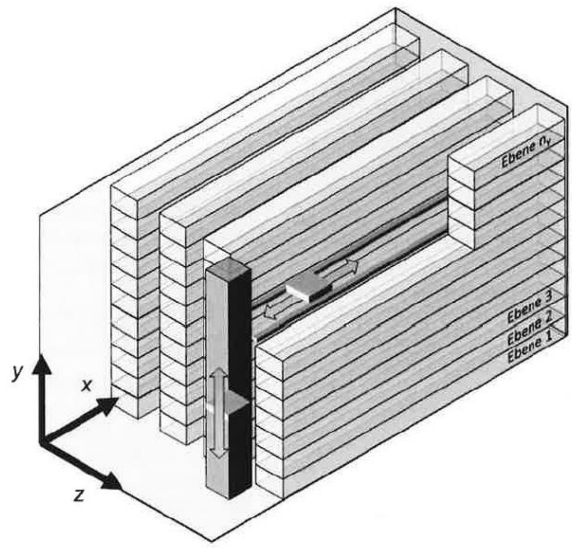


Figure 36: Coordinate system of horizontal carousel system

[54] ([VDI14], p. 4)

2.5.2 Calculation of throughput

2.5.2.1 Mean cycle time and throughput according to VDI 2692

The main goal of the calculation that the "Verein Deutscher Ingenieure" (VDI) published in the guideline VDI 2692 called "Shuttle-Systeme für Kleinbehälterlagerung" is an estimation of a possible throughput that a shuttle system is capable of under certain assumptions. In contrast to other guidelines and standards, the calculation of throughput and mean cycle times is split into a separate analysis of the lift and the shuttle vehicle. In addition to this significant cycle times, standby times that occur (e.g. waiting for the lift) have to be considered. These times are highly dependent on the numbers of unit loads that are stored and retrieved at a certain point in time as well as on control strategies like the storage assignment policies, order scheduling or request sequencing. Hence, the guideline assumes that only one lift on the face-side is used, all storage compartments are single deep and the usage of each compartment is randomly distributed. The derivation is taken from ([VDI14]).

Mean cycle time of a container lift

Shuttle systems that use a container lift as hoisting device usually have two lifts per aisle, one executing input and the other output operations. Hence, container lifts always conduct single command cycles and the corresponding empty (unloaded) driving. The general motion-sequence for the storage and retrieval process is shown in Figure 37.

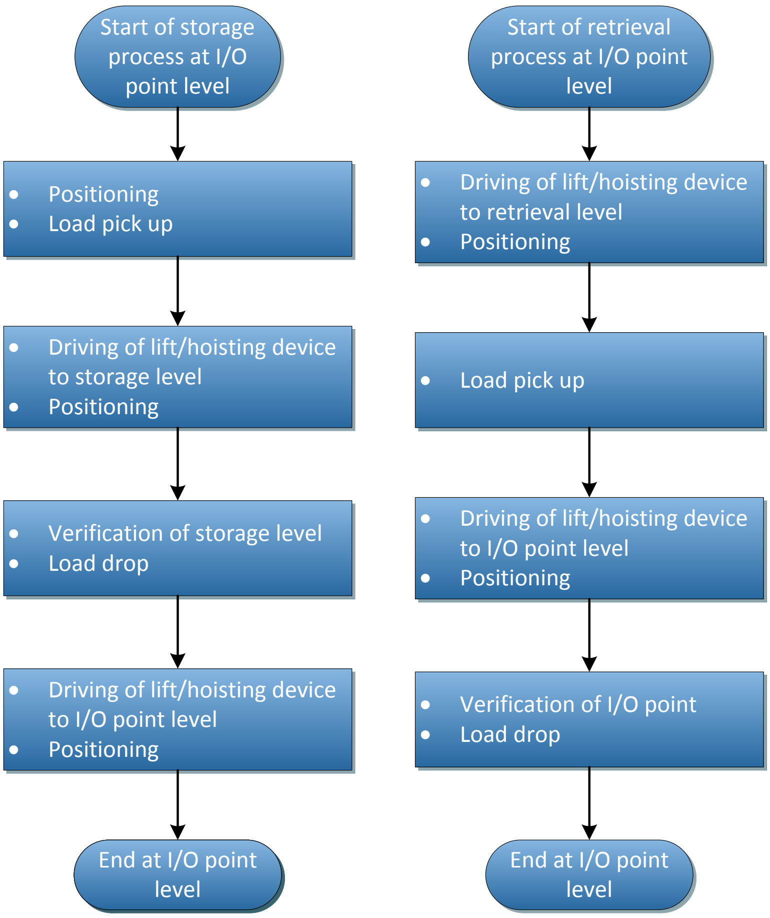


Figure 37: Motion-sequence of container lift for storage and retrieval

The mean cycle time for a storage or retrieval single cycle can be calculated following this equation:

$$t_{SE,y} = 2 * (t_{FE,y} + t_{G,y} + t_{P,y}) \quad \text{Equation 54}$$

The mean travel time $t_{FE,y}$ can be calculated as the sum of the weighted travel times between the I/O point level and all other levels $k = 1, 2, \dots, n_y$. The probability of driving to a certain level is equally distributed and is

$$p = \frac{1}{n_y} \quad \text{Equation 55}$$

If the distance between each level is $l_y = const.$ and the distance between the I/O level and levels $k = 1$ equals l_{EAP}, the mean cycle times accounts to:

$$t_{FE,y} = \sum_{k=1}^{n_y} \frac{1}{n_y} * t(|l_{EAP} + (k-1) * l_y|) \quad \text{Equation 56}$$

$$t_{FE,y} = \frac{1}{n_y} * \sum_{k=1}^{n_y} * t(|l_{EAP} + (k-1) * l_y|) \quad \text{Equation 57}$$

Table 20: Nomenclature of cycle times for a single cycle of a container lift

Nomenclature	
$t_{SE,y}$	Mean cycle time for a single cycle done by a lift
$t_{FE,y}$	Mean travel time for a single cycle done by a lift
$t_{G,y}$	Mean cycle time for load handling device of a lift
$t_{p,y}$	Downtime (positioning, etc.)
l_y	Distance between two levels in y-coordinate
l_{EAP}	Distance between I/O point and first level in y-coordinate
n_y	Amount of storage levels in y-coordinate

Mean cycle time of a vehicle lift

In contrast to the previously mentioned systems, shuttle systems that use a vehicle lift as hoisting device only have one lift per aisle. Hence, vehicle lifts always conduct dual command cycles. After unloading the bin at a the storage compartment, an empty travel to the retrieval level for loading another unit load is conducted. By combining such single cycle commands, the amount of empty travel is reduced. The general motion-sequence for the storage and retrieval process is shown in Figure 38.

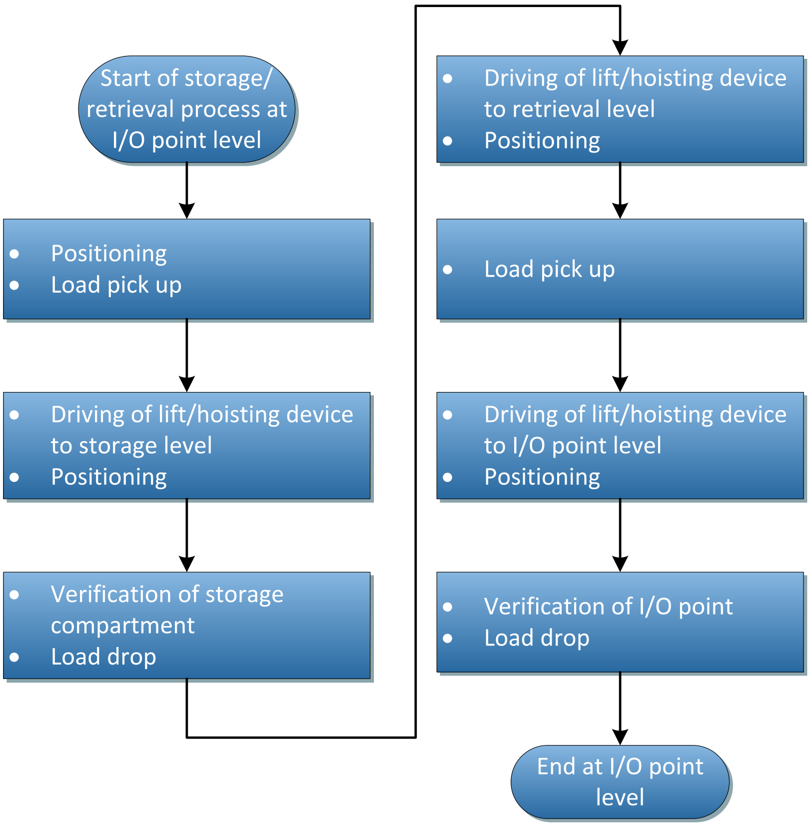


Figure 38: Motion-sequence of a vehicle lift for storage and retrieval

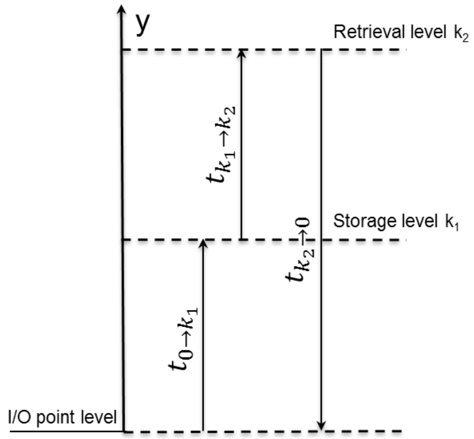
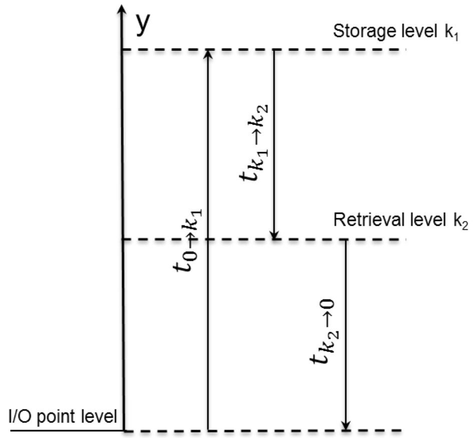
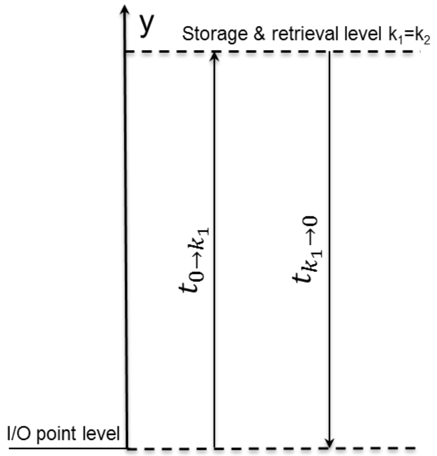
Depending on the position of the storage and retrieval levels one has to differentiate between three cases, that are depicted in Table 22.

Table 21: Nomenclature of cycle times for a double cycle of a vehicle lift

Nomenclature	
$t_{SE,y}$	Mean cycle time for a single cycle done by a lift
$t_{FE,y}$	Mean travel time for a single cycle done by a lift
$t_{G,y}$	Mean cycle time for load handling device of a lift
$t_{G,x}$	Mean cycle time for load handling device of shuttle vehicle
$t_{p,x}$	Downtime (positioning, etc.) of shuttle vehicle
$t_{p,y}$	Downtime (positioning, etc.) of lift
l_y	Distance between two levels in y-coordinate
l_{EAP}	Distance between I/O point and first level in y-coordinate
n_y	Amount of storage levels in y-coordinate

The total cycle consists of three parts, the movement from the I/O point to level $k = 1$ where the storage compartment is located, an empty travel to the retrieval levels $k = 2$ where the second container is picked up and finally the travel back to the I/O point.

Table 22: Three different cases of travel between storage and retrieval level[55]

Cases	
$k_1 < k_2$	
$k_1 > k_2$	
$k_1 = k_2$	

[55] ([VDI14], p. 11)

The mean travel times for movement number one and three can be easily described using Equation 39 for single commands. The second movement necessitates a combinative approach that determines the probability $\omega_{m,y}$ of a level change with $m = |k_1 - k_2|$ levels in-between.

The probability of not changing the level can be described with:

$$\omega_{0,y} = \frac{n_y}{n_y^2} = \frac{1}{n_y} \qquad \text{Equation 58}$$

whereas the other possible combinations with $m = 1, 2, \ldots, n_y - 1$ movements are calculated by using:

$$\omega_{m,y} = \frac{2 * (n_y - m)}{n_y^2} \qquad \text{Equation 59}$$

The mean travel time for a double cycle of the vehicle lift thus sums up to:

$$t_{FD,y} = 2 * t_{FE,y} + \sum_{m=1}^{n_y - 1} \omega_{m,y} * t(m * l_y) \qquad \text{Equation 60}$$

Last but not least, the total mean cycle time that consists of the travel times of the lift, the cycle time for loading and unloading both the container onto the vehicle and the vehicle onto the lift platform, as well as all downtimes that are necessary to position the vehicle and lift.

$$t_{SD,y} = t_{FD,y} + 2 * t_{G,x} + 2 * t_{G,y} + (3 * \omega_{0,y}) * t_{p,y} \qquad \text{Equation 61}$$

Mean cycle time of a vehicle

The mean cycle time of a shuttle considers solely the horizontal movement in a single level. Again single or dual command cycles can be executed. This is identical for both shuttle systems with container and vehicle lift. The calculation for the lift can be adopted accordingly in order to describe the mean cycle-time for a double cycle performed by shuttle mathematically:

$$t_{SD,x} = t_{FD,x} + 2 * t_{G,x} + 2 * t_{G,x} + (3 * \omega_{0,x}) * t_{p,x} \qquad \text{Equation 62}$$

Table 23: Nomenclature of cycle times for a dual command of a shuttle vehicle

Nomenclature	
$t_{SD,x}$	Mean cycle time for a double cycle by a shuttle vehicle
$t_{FD,x}$	Mean travel time for a double cycle by a shuttle vehicle
$t_{FE,x}$	Mean travel time for a single cycle by a shuttle vehicle
$t_{G,x}$	Mean cycle time for load handling device of shuttle vehicle
$t_{p,x}$	Downtime (positioning, etc.)
l_x	Distance between two storage compartments in x-coordinate
$\omega_{0,x}$	Probability of approaching any storage compartment the first time

$\boldsymbol{\omega_{m,x}}$	Probability of changing to another storage compartment for storage and retrieval
$\boldsymbol{n_x}$	Amount of storage compartment in x-coordinate

The cycle time for driving a single cycle can be calculated analog to Equation 57:

$$t_{FE,x} = \frac{1}{n_x} * \sum_{k=1}^{n_x} t((k-1) * l_x)$$ Equation 63

The probability of changing the storage compartment between storage and retrieval with a rack of m locations, is given with the equations:

$$\omega_{0,x} = \frac{\mathrm{n_x}}{\mathrm{n_x^2}} = \frac{1}{\mathrm{n_x}}$$ Equation 64

$$\omega_{m,x} = \frac{2 * (n_x - m)}{n_x^2}$$ Equation 65

whereas the number of locations in-between is $m = 1, 2, \dots, n_x - 1$.

The travel time for driving a double cycle can be calculated using:

$$t_{FD,x} = 2 * t_{FE,x} + \sum_{m=1}^{n_x - 1} \omega_{m,x} * t(m * l_x)$$ Equation 66

In general, the motion sequences of both the vehicle and the lift are the same as the sequences of the x- and y-coordinate of a miniload. The trapezoid velocity curve is depicted in Figure 28. Thus Equation 15 to Equation 22 are valid:

Trapezoid movement:

$$l_x \geq \frac{{v_{x,y}}^2}{a_{x,y}}$$ Equation 67

$$v = v_{max}; a = const.$$ Equation 68

$$l_{x,y} = \int_0^{t_{l_{x,y}}} v(t)dt = v * t_{l_{x,y}} - \frac{{v_{x,y}}^2}{a_{x,y}}$$ Equation 69

$$t_{l_{x,y}} = \frac{l_{x,y}}{v_{x,y}} + \frac{v_{x,y}}{a_{x,y}}$$ Equation 70

Triangular movement:

$$l_{x,y} < \frac{{v_{x,y}}^2}{a_{x,y}}$$ Equation 71

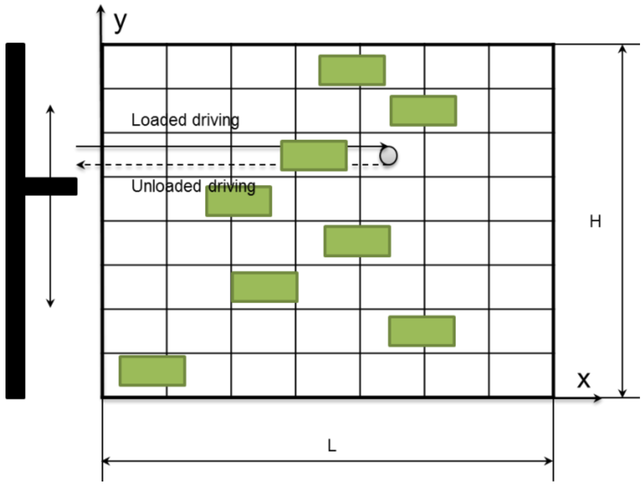
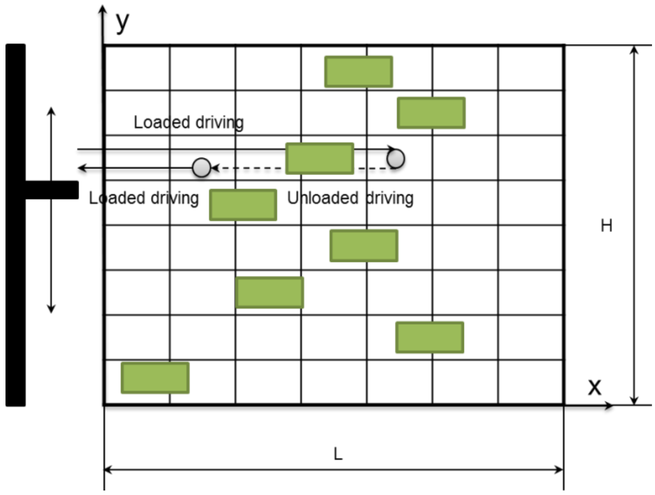
$$v \neq v_{max}$$ Equation 72

$$l_{x,y} = a_{x,y} * t_{l_{x,y}}^2$$ Equation 73

$$t_{l_{x,y}} = \sqrt{\frac{l_{x,y}}{a_{x,y}}}$$ Equation 74

The time needed for goods pickup and dropping $t_{G,x}$ as well as the time $t_{p,x}$ needed for positioning and controlling can be considered as constant, hence, the cycle time is essentially influenced by the travel-dependend time needed to travel to all storage compartments.

Table 24: SC and DC storage and retrieval cycles of a shuttle vehicle[56]

<table>
<tr><th colspan="2">Cases</th></tr>
<tr><td>
</td><td>SC storage or retrieval cycle</td></tr>
<tr><td>
</td><td>DC storage & retrieval cycle</td></tr>
</table>

[56] ([VDI14], p. 11)

3 Energy efficiency indicator models

3.1 Literature

Figure 39 provides a good overview of all literature dealing with energy efficiency for storage systems that is currently available. In the following chapter an excerpt of literature with particular relevance for energy efficiency indicator models is featured. Further literature, which is depicted in Figure 39 but focuses on energy demand and its reduction in general is not described in more detail, since this would go beyond the scope of this thesis.[57]

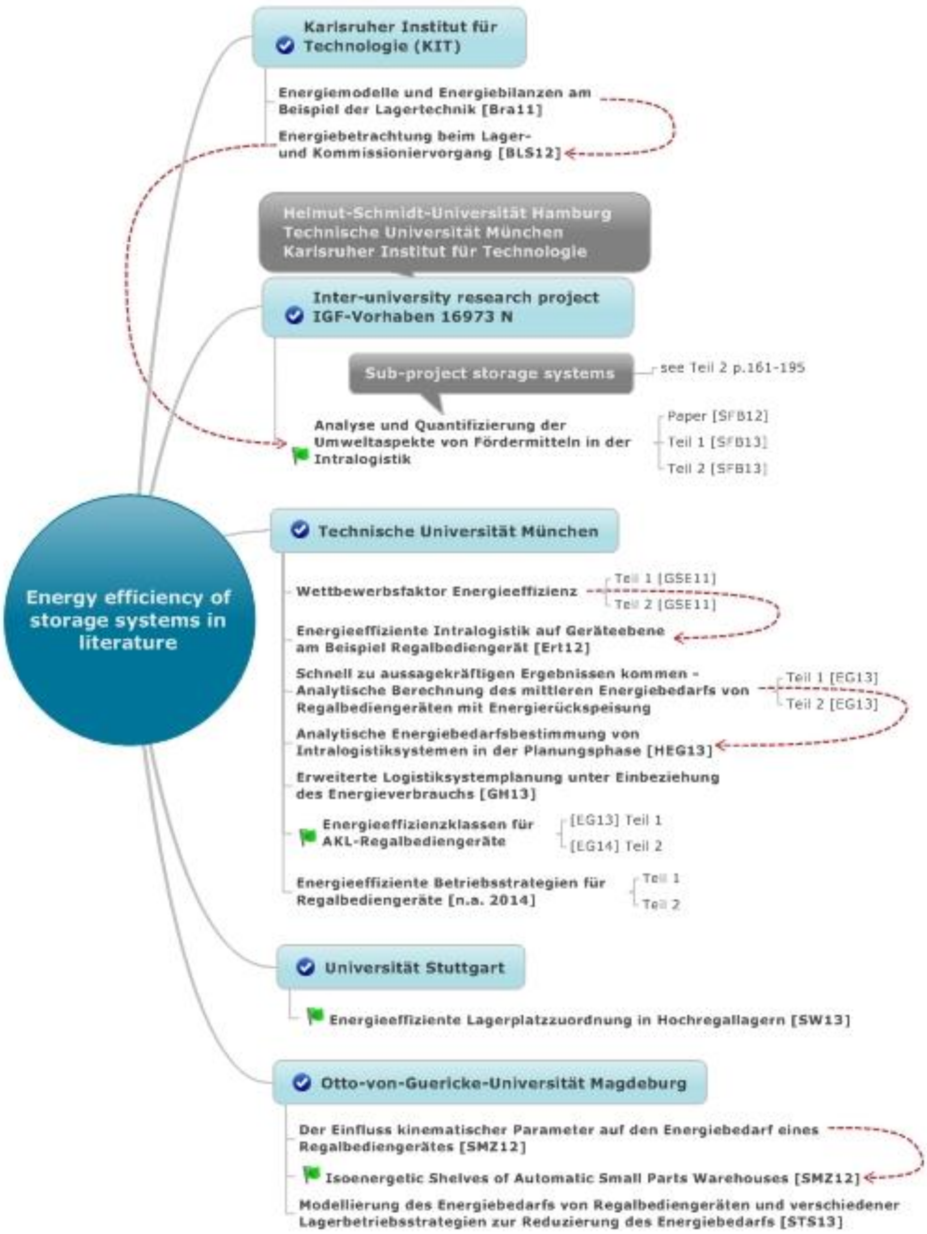


Figure 39: Overview of energy efficiency of storage systems in literature

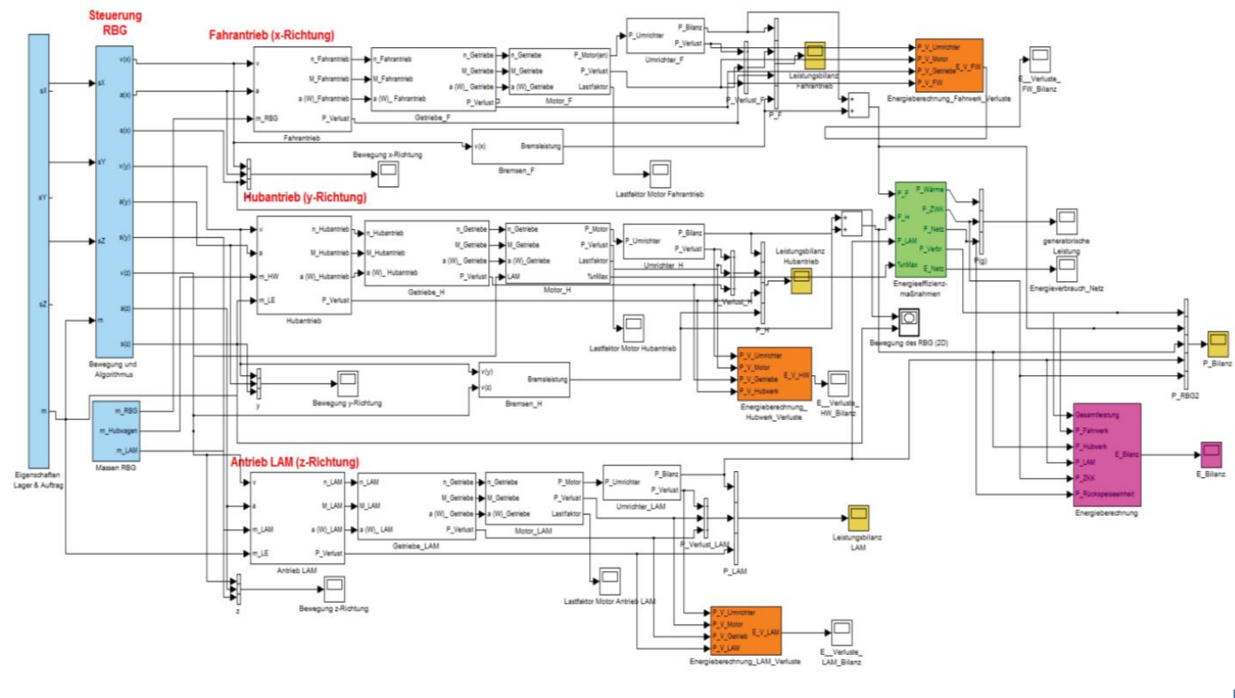
[57] Refer to the listed literature for further and more detailed information

3.1.1 Karlsruher Institut für Technologie (KIT)

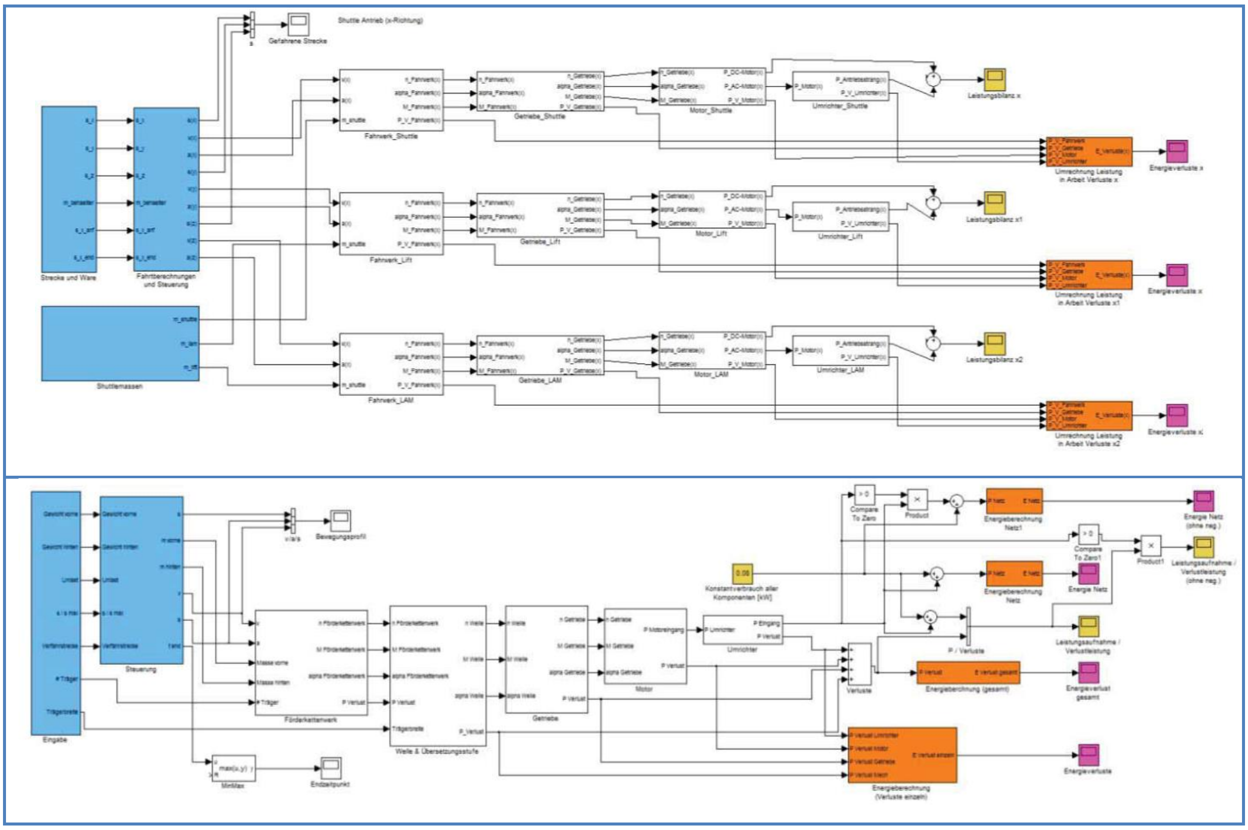
The research activities of the KIT, which were published in ([Bra11]), ([Sch11]), ([BLS12]) and ([SFB12]) are part of an interdisciplinary research project called „IGF-Vorhaben 16973 N Analyse und Quantifizierung der Umweltauswirkungen von Fördermitteln in der Intralogistik“ (Full content: [SFB13a]; [SFB13b]) The major aim of this research project is to reveal environmental impacts of material handling equipment in the storage and retrieval process by considering the environmental aspects over the whole life cycle. ([BLS12], p. 1)

In a first step, a catalog of environmental impacts has been developed. The impacts that were found for each material handling technology were analyzed throughout the product life cycle in order to find out their magnitude. A particular focus was directed on revealing the interference of each material handling technique in a system. The quantification of the environmental aspects and their impacts was done by using the EcoReport Tool that is provided by the European Commission. It turned out that the utilization phase has a major impact in particular. As a consequence, analytical models for several material handling systems were developed, which enable the determination of a performance curve. Furthermore, the total energy demand can be derived from these curves since $E = \int P(t)$. Stacker cranes, shuttle systems and horizontal carousel systems are described in more detail.

Table 25: Analytical SIMULINK models[58]

Analytical SIMULINK models for stacker cranes, shuttle systems and horizontal carousel systems


58 ([SFB13b], p. 177; 179)



The SIMULINK models that are depicted in Table 25 can calculate information regarding performance and energy demand by providing characteristic factors like velocity, acceleration or mass. In addition, these models were evaluated by taking measurements.

Based on these findings, several actions for improving the energy efficiency of stacker cranes were presented in a showcase. These considerations include energy recuperation, the usage of more energy efficient drivetrains or the variation of the characteristic factors of a stacker crane. The analyses assume an equal distribution across the front side of the rack and consider a mean energy demand. In Figure 40 the green area represents storage compartments that can be reached using less than the mean energy demand of the racks front, while the red area includes compartments that consume more energy.

Finally, methodologies to evaluate the environmental impacts are discussed in ([SFB13b], S. 191–192). In accordance with the effMFS project indicator models are introduced. Both approaches from KIT and TU Graz are not the same but quite similar. The energy efficiency is defined as:

$$K_{Efficiency} = \frac{Output\ of\ a\ performance\ or\ process}{Energy\ input} \quad \text{Equation 75}$$

Or in other words:

$$K_{Efficiency} = \frac{Environmental\ aspect}{Logistic\ performance} \quad \text{Equation 76}$$

For stacker cranes several combinations of indicators were proposed:

$$K_{Efficiency1} = \frac{Specific\ energy\ demand}{Throughput * transported\ mass}$$ Equation 77

$$K_{Efficiency2} = \frac{Specific\ energy\ demand}{Traveled\ distance\ (x, y, z) * transported\ mass}$$ Equation 78

$$K_{Efficiency3} = \frac{Specific\ energy\ demand}{Traveled\ distance\ (x, y, z)}$$ Equation 79

$$K_{Efficiency4} = \frac{Specific\ energy\ demand * throughput}{Traveled\ distance\ (x, y, z)}$$ Equation 80

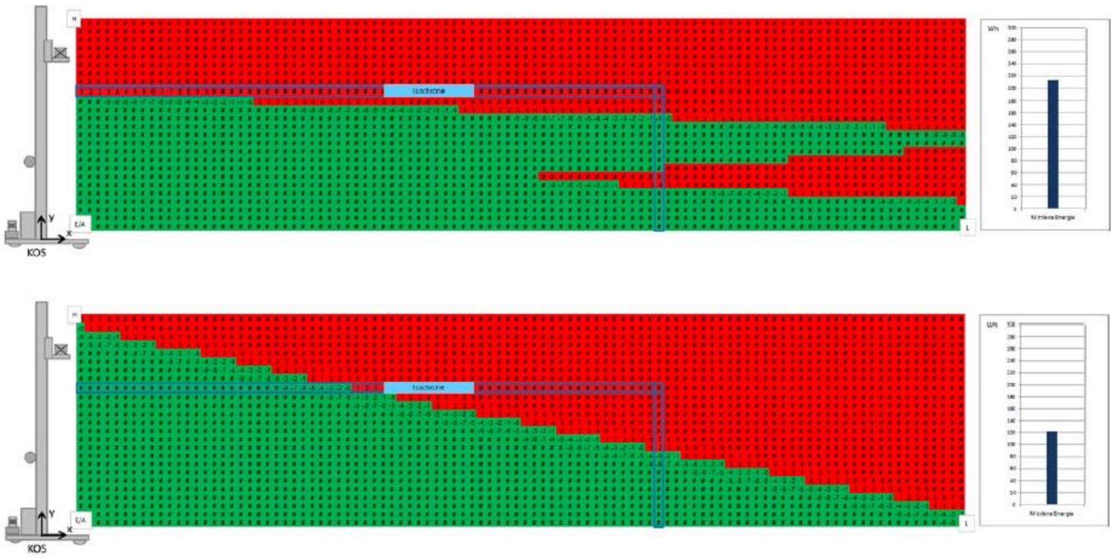


Figure 40: Mean energy demand of SC cycle in stacker crane with intermediate circuit connection (above) or energy recuperation module (beneath)[59]

3.1.2 Technische Universität München

The two-part paper ([EG13]; [EG14]) describes an initial contribution in form of a concept to describe a comparative assessment of stacker cranes regarding their energy efficiency. The aim of the paper is to develop a definition of energy efficiency classes and hence, it is strongly modelled to the guideline VDI 4707 ([VDI09]), that is used to describe the energy efficiency of elevator systems. The approach that the authors use for the concept is classified into three subtasks: ([EG13], p. 8)

- Determination of the actual energy demand E_{ges} for a representative reference cycle
- Accumulation of a specific energy efficiency indicator K_{EE}
- Development of a classification system for energy efficiency of stacker cranes with system-dependent limiting values

The total energy demand is defined as follows:

$$E_{ges} = \bar{P}_{brach} * T_{brach} + \bar{P}_{nutz} * T_{nutz}$$ Equation 81

[59] ([BLS12], p. 5)

$$E_{ges} = \bar{P}_{brach} * T_{brach} + \frac{E_{nutz}}{t_{nutz}} * T_{nutz}$$ Equation 82

The fractions of time T_{brach} (standby period) and T_{nutz} (usage period) are defined according to ([VDI09]) by introducing usage categories (see Table 26).

Table 26: Definition of usage categories for stacker cranes[60]

Usage category	1	2	3	4	5
Intensity of usage	very infrequent	infrequent	occasional	frequent	very frequent
Usage period [%]	10 >0-20	30 >20-40	50 >40-60	70 >60-80	90 >80-100
Standby period [%]	90	70	50	30	10

Table 27: Calculation of reference point coordinates in dependence of the shelf unit parameter[61]

	$w < 1$	$w > 1$
x_{REF}	$\frac{1}{2} * L * \left(1 + \frac{1}{3} * w^2\right)$	$\frac{1}{2} * L * \left(w + \frac{1}{3 * w}\right)$
y_{REF}	$\frac{1}{2} * \frac{v_{ym}}{v_{xm}} * L * \left(1 + \frac{1}{3} * w^2\right)$	$\frac{1}{2} * \frac{v_{ym}}{v_{xm}} * L * \left(w + \frac{1}{3 * w}\right)$

The reference cycle for determining the mean power consumption during usage $\bar{P}_{nutz}$ is defined as single command cycle and uses the intercept point of the isochrones as reference point. The cycle time of this reference point resembles the mean cycle time of a SC cycle, but the necessary power demand does not resemble the mean power demand of a SC cycle. However, the authors state that the reference point is suited for comparison, since the mean energy demand adapts accordingly when varying the rack dimension. The calculation of the coordinates of the reference point is shown in Table 27.

Scaling the total energy demand according to the reference cycle, the total energy can be calculated as follows:

$$E_{ges,RS} = \bar{P}_{brach} * T_{brach} * \frac{t_{nutz}}{T_{nutz}} + E_{nutz}$$ Equation 83

Like with the other definitions throughout literature the energy efficiency is defined as:

$$K_{EE} = Energy\ efficiency = \frac{effort}{benefit} = \frac{\Psi}{\Phi}$$ Equation 84

60 ([EG13], p. 9)
61 ([EG13], p. 9)

The effort Ψ correlates to $E_{ges,RS}$, whereas the benefit Φ is determined by the payload, the throughput and the area of the rack that is served by the stacker crane.

$$\Phi = \mathrm{m_{nutz}} * \lambda * \mathrm{A_w} \quad \text{Equation 85}$$

The energy efficiency indicator can now be determined as:

$$K_{EE} = \frac{\Psi}{\Phi} = \frac{P_{brach} * T_{brach} * t_{nutz}^2}{T_{nutz} * m_{nutz} * L * H} + \frac{E_{nutz} * t_{nutz}}{m_{nutz} * L * H} \quad \text{Equation 86}$$

In order to evaluate the efficiency of the both the usage and standby period, the authors split the energy efficiency into:

$$K_{EE,nutz} = \frac{E_{nutz} * t_{nutz}}{m_{nutz} * L * H} \quad \text{Equation 87}$$

$$K_{EE,brach} = P_{brach} \quad \text{Equation 88}$$

In ([EG14]) the authors define energy demand classes to evaluate the usage period as well as the standby period. This forms the basis for a total energy efficiency class system. The limiting values that are used for each class are arranged in geometric series, in the same way as ([VDI09]) suggests. The geometric series are defined in the following scheme:

- Standby period:

$$a_1 = 0{,}075kW \qquad a_{i+1} = 2 * a_i \quad \text{Equation 89}$$

- Usage period:

$$b_1 = 7{,}5\frac{mWh * s}{kg * m^2} \qquad b_{i+1} = 1{,}5 * b_i \quad \text{Equation 90}$$

The energy demand classes are shown in Table 28 and

Table 29, while Figure 41 shows the energy efficiency class for a total evaluation.

Table 28: Energy demand classes for standby period[62]

Class	A	B	C	D	E	F	G
$K_{EE,brach}$ [kW]	$\leq 0{,}075$	$\leq 0{,}15$	$\leq 0{,}3$	$\leq 0{,}6$	$\leq 1{,}2$	$\leq 2{,}4$	$\geq 2{,}4$

Table 29: Energy demand classes for usage period[63]

Class	A	B	C	D	E	F	G
$K_{EE,nutz}$ [(mWh*s)/(kg*m²)]	$\leq 7{,}5$	$\leq 11{,}25$	$\leq 16{,}88$	$\leq 25{,}31$	$\leq 37{,}97$	$\leq 56{,}95$	$\geq 56{,}95$

[62] ([EG14], p. 10)
[63] ([EG14], p. 11)

Energie-effizienzklasse	Nutzungskategorie 1	2	3	4	5
A	$7{,}5 + \frac{75W \cdot 0{,}9 \cdot t_{nutz}^2}{0{,}1 \cdot m_{nutz} \cdot L \cdot H}$	$7{,}5 + \frac{75W \cdot 0{,}7 \cdot t_{nutz}^2}{0{,}3 \cdot m_{nutz} \cdot L \cdot H}$	$7{,}5 + \frac{75W \cdot 0{,}5 \cdot t_{nutz}^2}{0{,}5 \cdot m_{nutz} \cdot L \cdot H}$	$7{,}5 + \frac{75W \cdot 0{,}3 \cdot t_{nutz}^2}{0{,}7 \cdot m_{nutz} \cdot L \cdot H}$	$7{,}5 + \frac{75W \cdot 0{,}1 \cdot t_{nutz}^2}{0{,}9 \cdot m_{nutz} \cdot L \cdot H}$
B	$11{,}25 + \frac{150W \cdot 0{,}9 \cdot t_{nutz}^2}{0{,}1 \cdot m_{nutz} \cdot L \cdot H}$	$11{,}25 + \frac{150W \cdot 0{,}7 \cdot t_{nutz}^2}{0{,}3 \cdot m_{nutz} \cdot L \cdot H}$	$11{,}25 + \frac{150W \cdot 0{,}5 \cdot t_{nutz}^2}{0{,}5 \cdot m_{nutz} \cdot L \cdot H}$	$11{,}25 + \frac{150W \cdot 0{,}3 \cdot t_{nutz}^2}{0{,}1 \cdot m_{nutz} \cdot L \cdot H}$	$11{,}25 + \frac{150W \cdot 0{,}1 \cdot t_{nutz}^2}{0{,}9 \cdot m_{nutz} \cdot L \cdot H}$
C	$16{,}88 + \frac{300W \cdot 0{,}9 \cdot t_{nutz}^2}{0{,}1 \cdot m_{nutz} \cdot L \cdot H}$	$16{,}88 + \frac{300W \cdot 0{,}7 \cdot t_{nutz}^2}{0{,}3 \cdot m_{nutz} \cdot L \cdot H}$	$16{,}88 + \frac{300W \cdot 0{,}5 \cdot t_{nutz}^2}{0{,}5 \cdot m_{nutz} \cdot L \cdot H}$	$16{,}88 + \frac{300W \cdot 0{,}3 \cdot t_{nutz}^2}{0{,}7 \cdot m_{nutz} \cdot L \cdot H}$	$16{,}88 + \frac{300W \cdot 0{,}1 \cdot t_{nutz}^2}{0{,}9 \cdot m_{nutz} \cdot L \cdot H}$
D	$25{,}31 + \frac{600W \cdot 0{,}9 \cdot t_{nutz}^2}{0{,}1 \cdot m_{nutz} \cdot L \cdot H}$	$25{,}31 + \frac{600W \cdot 0{,}7 \cdot t_{nutz}^2}{0{,}3 \cdot m_{nutz} \cdot L \cdot H}$	$25{,}31 + \frac{600W \cdot 0{,}5 \cdot t_{nutz}^2}{0{,}5 \cdot m_{nutz} \cdot L \cdot H}$	$25{,}31 + \frac{600W \cdot 0{,}3 \cdot t_{nutz}^2}{0{,}7 \cdot m_{nutz} \cdot L \cdot H}$	$25{,}31 + \frac{600W \cdot 0{,}1 \cdot t_{nutz}^2}{0{,}9 \cdot m_{nutz} \cdot L \cdot H}$
E	$37{,}97 + \frac{1200W \cdot 0{,}9 \cdot t_{nutz}^2}{0{,}1 \cdot m_{nutz} \cdot L \cdot H}$	$37{,}97 + \frac{1200W \cdot 0{,}7 \cdot t_{nutz}^2}{0{,}3 \cdot m_{nutz} \cdot L \cdot H}$	$37{,}97 + \frac{1200W \cdot 0{,}5 \cdot t_{nutz}^2}{0{,}5 \cdot m_{nutz} \cdot L \cdot H}$	$37{,}97 + \frac{1200W \cdot 0{,}3 \cdot t_{nutz}^2}{0{,}7 \cdot m_{nutz} \cdot L \cdot H}$	$37{,}97 + \frac{1200W \cdot 0{,}1 \cdot t_{nutz}^2}{0{,}9 \cdot m_{nutz} \cdot L \cdot H}$
F	$56{,}95 + \frac{2400W \cdot 0{,}9 \cdot t_{nutz}^2}{0{,}1 \cdot m_{nutz} \cdot L \cdot H}$	$56{,}95 + \frac{2400W \cdot 0{,}7 \cdot t_{nutz}^2}{0{,}3 \cdot m_{nutz} \cdot L \cdot H}$	$56{,}95 + \frac{2400W \cdot 0{,}5 \cdot t_{nutz}^2}{0{,}5 \cdot m_{nutz} \cdot L \cdot H}$	$56{,}95 + \frac{2400W \cdot 0{,}3 \cdot t_{nutz}^2}{0{,}7 \cdot m_{nutz} \cdot L \cdot H}$	$56{,}95 + \frac{2400W \cdot 0{,}1 \cdot t_{nutz}^2}{0{,}9 \cdot m_{nutz} \cdot L \cdot H}$
G	$>56{,}95 + \frac{2400W \cdot 0{,}9 \cdot t_{nutz}^2}{0{,}1 \cdot m_{nutz} \cdot L \cdot H}$	$>56{,}95 + \frac{2400W \cdot 0{,}7 \cdot t_{nutz}^2}{0{,}3 \cdot m_{nutz} \cdot L \cdot H}$	$>56{,}95 + \frac{2400W \cdot 0{,}5 \cdot t_{nutz}^2}{0{,}5 \cdot m_{nutz} \cdot L \cdot H}$	$>56{,}95 + \frac{2400W \cdot 0{,}3 \cdot t_{nutz}^2}{0{,}7 \cdot m_{nutz} \cdot L \cdot H}$	$>56{,}95 + \frac{2400W \cdot 0{,}1 \cdot t_{nutz}^2}{0{,}9 \cdot m_{nutz} \cdot L \cdot H}$

Figure 41: Energy efficiency classes and the corresponding usage categories[64]

Although this concept is one of the most advanced assessment strategies in intralogistics, it has a unfavorable side effect. On the one hand, using the dimensions of the rack as part of the indicator model is a reasonable approach to compensate the decrease of energy efficiency with greater dimensions but on the other hand it causes the indicator to be very variable. This fact can be seen in Figure 42, which shows a parameter variation of L and H.

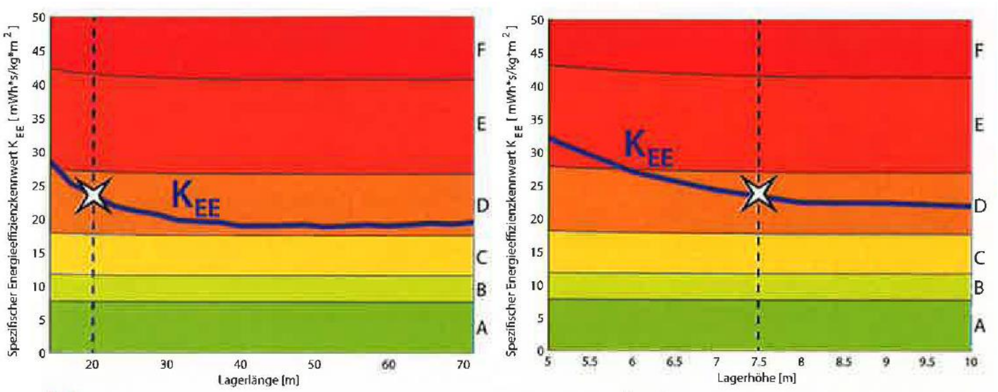


Figure 42: Specific energy efficiency indicator while varying the parameters L (left) and H (right)[65]

[64] ([EG14], p. 12)

3.1.3 Universität Stuttgart

In ([SW13]) an energy efficient storage assignment strategy for stacker cranes is presented. The main focus of this new strategy is to maintain the throughput requirements on the one hand and to decrease energy demand on the other hand. Previous strategies that decreased the power consumption always led to a reduced throughput. Therefore the new storage compartment assignment policy is contrasted and compared to state of the art policies, as described in chapter 2.2.3 of this master's thesis. ([SW13], p. 1)

At the beginning of the paper the authors define efficiency and describe ways to maximize the same on the basis of the economical principle:

$$Efficiency = \frac{target\ gain}{necessary\ means\ to\ achieve\ goal}$$ Equation 91

Essentially three possibilities regarding optimization do exist:

- Maximum principle: A defined use of necessary means is to generate the maximum gain possible
- Minimum principle: A defined gain is to be achieved by providing the minimum necessary means
- Maximin principle: By providing a minimum of means the maximum of gain is to be acquired

In the case of automated storage and retrieval systems the authors translate the target gain into the throughput while the means to achieve the goal is the necessary energy input.

$$Energyeffiency = \frac{storage\ or\ retrievals}{unit\ of\ energy}$$ Equation 92

Previous approaches to reduce the mechanical energy demand and to increase the energy efficiency respectively are further identified and categorized according to this 4 groups:

- Mechanical design
    - Minimization of moving mass
    - Reduction of rotational radii
    - Reduction of friction
- Electrical design
    - Linkage of intermediate circuit
    - Energy recuperation/regeneration
- Operational strategies (movement)
    - Programming of the AS/RS control unit:
        - velocity and acceleration is adapted according to load (payload, throughput, etc.)
        - consideration of areas critical for travel- and hoist time
- Storage assignment policy

[65] ([EG14], p. 11)

A simulation study according to VDI 3633-1 was compiled using PLANT SIMULATION. In order to assess the storage assignment strategies based on the mean cycle time and energy demand, a mechanical energy model was implemented, which calculates the kinetic, potential and friction energy. The basis simulation is a single wide, single deep stacker crane and a rack with storage compartments of equal size. The simulation model assumes:

- complete conversion of kinetic energy into friction losses
- increase of kinetic or potential energy for movements in x- and y-axis
- consideration of friction coefficient along the x- and y-axis
- calculation of energy demand for storage or retrieval; travels in-between are not includes since they are part of the scheduling strategy
- payloads ranging from 100 to 1200 kg
- dwell time according to a β-distribution
- storage and retrievals are performed using double cycles
- utilization degree 0,87
- storage assignment policies:
    - RND: random storage assignment, no zoning
    - COL1: closest open location assignment, no zoning
    - COL2: closest open location assignment within one of two zones
    - DYN: dynamic zoning according to ([Gla08]); assignment of storage location by comparing the quantile of travel time to the storage compartment to the quantile of dwell time of an unit load
    - MVI-0 and MVI-10: new strategies develop by the authors

The newly developed storage assignment strategies MVI-0 and MVI-10 are based on considering the isochrones in combination with an effective mass distribution within the rack for energy efficient storage processes. The mass distribution endeavors to store heavy unit loads without the need of lifting movement, while light-weight unit loads are favored to be stored in compartments with a greater vertical distance to the I/O point. Since all storage compartments along isochrones possess the same travel times but do require different power dependent on the payload of the unit load, an algorithm was developed which identifies the suitability of each compartment. This is achieved by introducing penalty indicators that resemble the difference of the energy needed to store a heavy (1200kg) versus a light-weight (100kg) unit load. The assignment of a compartment using the MVI strategies is performed in 5 steps: ([SW13], p. 8)

- Determination of a storage location using the DYN strategy by ([Gla08])
- Consideration of all near-neighbor locations for optimal mass distribution
- Sorting of all possible optimal compartments using the penalty indicator in descending order
- Calculation of an index resembling the ideal location by multiplying the mass quantile of the unit load with the number of optimal storage compartments
- Assignment of storage location by choosing the compartment with the minimum deviation of the penalty indicator of the ideal and all possible locations

Table 30 lists the results of the simulation study after 50000 storage and retrieval processes.

Table 30: Simulation results[66]

#	Policy	Mean travel time [s]	Mean energy demand [Wh]	Energy savings compared to #1 [%]
1	RND	54,4	162,3	-
2	COL1	51,5	152,4	6,10
3	COL2	44,6	131,8	18,79
4	DYN	42,9	125,8	22,49
5	MVI-0	42,9	123,8	23,72
6	MVI-10	42,3	115,4	28,90

3.1.4 Otto-von-Guericke-Universität Magdeburg

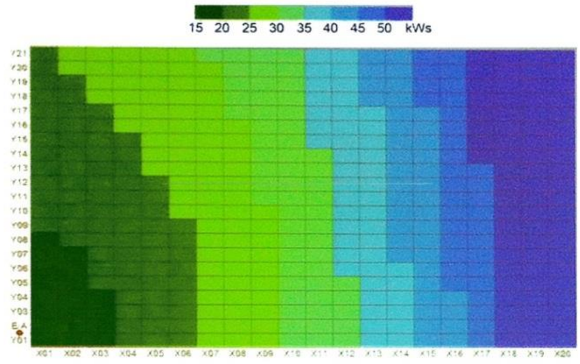
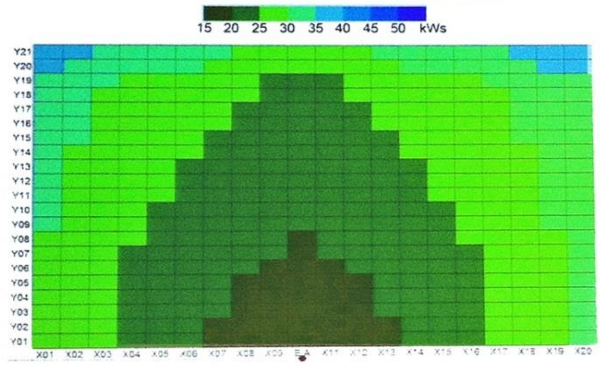
From the four levers to increase the energy efficiency (mechanical design, electrical design, operational strategies or storage assignment policy), which have already been described, the last two points are in the focus of the paper ([SMZ12]). In order to quantify the potential of configuring more energy efficient strategies, single movements are analyzed over time in terms of power consumption. Furthermore, state of the art storage strategies were tested concerning the average energy demand. As a major result *isoenergetic shelves* were deduced, which can be reached using the same amount of energy.

In a first step, the influence of the starting point of each drivetrain was considered in conjunction with the two options for energy recovery (recovery into the public grid, DC intermediate circuit). Since a recovery into the grid is always related to losses, the direct usage of recovered energy by other appliances (e.g. the other drive train) is to be favored. Therefore, the movements of each drive need to be synchronized especially during acceleration and deceleration phases. This means that for example the lifting unit should not start until the driving unit is to recover energy by braking and vice versa. ([SMZ12], p. 4)

Based on the isochronal shelves, which can be reached within the same amount of time, the term *isoenergetic shelves* was developed. The definition is similar since isoenergetic shelves represent compartments that can be reached using the same energy input. Therefore a model out of the single experiments was developed which enables the calculation of the energy need for moving a unit load from one compartment to another. The model determines the energy need and the recovery of the operation cycles punctiform while it is possible to approximate and interpolate between sampling points. The total energy includes both the driving and lifting unit's energy needs and recovery, while the input to operate the fork and belt are considered as negligibly low. As can be seen in the figures in Table 31, the isoenergetic shelves vary depending on the I/O point (starting point of the movement) of the stacker crane. ([SMZ12], S. 5–6)

[66] ([SW13], p. 8)

Table 31: Isoenergetic shelves for different starting points[67]

Starting point X01/Y01	Starting Point X10/Y01
	

Several parameters, such as position of the I/O points, the velocities of the driving and lifting unit as well as the payload were identified as having substantial influence on the isoenergetic shelves. ([SMZ12], p. 8) These shelves can be seen as basis for further investigations regarding storage strategies. The following results were already obtained from the test bench:

Table 32: Energy input for different strategies[68]

Strategy	Average energy input	Note
Dedicated storage assignment	-	Not possible to measure the average energy need, as it is not possible to predict the transport orders
Transverse distribution	-	
FIFO/LIFO	-	
Random storage assignment (chaotic distribution)	18,1 kWs	Reference point X11/Y11
ABC	9,8 kWs	Based on five reference points that are defined using the area points of the ABC zones, SC operation and using the 80-20 rule
FEM 9.851 SC	37,8 kWs	Reference points X16/Y14 and X06/Y05 with I/O point at X21/Y02
FEM 9.851 DC	26,8 kWs	

67 ([SZ14])
68 ([SMZ12], p. 8)

3.2 Field of Observation

Assessing the content of chapter 1.4, it becomes obvious that there is a vast multitude of considerable varieties regarding the technical specifications and aspects as well as control strategies and areas of applications of automated storage and retrieval systems. It is therefore indispensable to define strict system boundaries. Otherwise a serious comparison can never be performed. In a first step, general system boundaries that are also used throughout the research project are presented. Subsequent, classification models are discussed that shall provide a framework to define the boundary conditions for the energy efficiency indicators of all three AS/RS types.

3.2.1 System boundaries of a material flow system (effMFS)

In ([HL12], S. 5–6), a level structure of material flow systems was presented which is the basic approach within the effMFS research project. The levels are arranged within a pyramid and comparable to the structure that can be found in Enterprise Resource Planning (ERP) systems and the like. In Figure 43 the different levels can be seen. The bottom of the pyramid consists of all basic components like electric drives and gears. All components summed up are representing a complete device. Hence, an automated storage and retrieval machine can be sub-summed under this category. The process level units several devices. At the top of the pyramid the whole facility is represented. Of special interest in this thesis is the device level, as the physical elements have to be analyzed in order to measure and calculate the energy efficiency indicators.

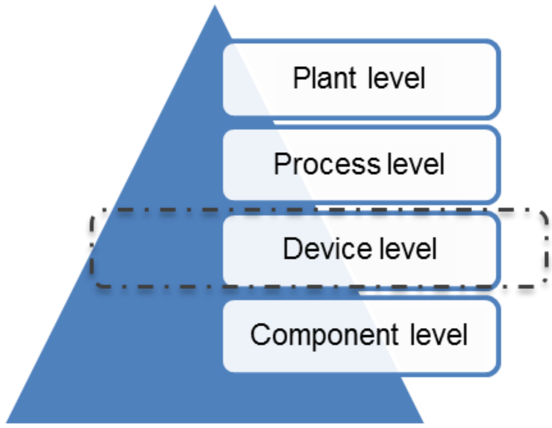


Figure 43: Levels of a material flow system

3.2.2 Assumptions for EEI-models

The following premises are the basis for all assumption and ongoing classifications in this chapter:

- The basic procedures for the energy efficiency classification shall be identical or comparable to the ones already used for conveyor technique in the effMFS research project.

- The measurement procedures shall be based or similar to a standard guideline like FEM 9.851 or VDI 3561 if possible.
- The energy efficiency indicator models must be designed in such a way that reproducible results can be obtained.
- The energy efficiency indicators models must be designed in such a way that both the measurement procedure and result are absolutely neutral, which means that they have to be independent from any technical solutions or manufacturer-specific implementation.

3.3 Classification concept of AS/RS for EEI-models – establishing equivalency

Although stacker cranes, horizontal carousel systems and shuttle systems essentially perform the same task, their technical nature is very different due to the different areas of application. For example there are distinct differences regarding the rack dimensions, type of unit load or numbers of storage compartments, as can be seen in Figure 44. Therefore it is vital to find and define a comparable basis so that each system is considered under the same conditions.

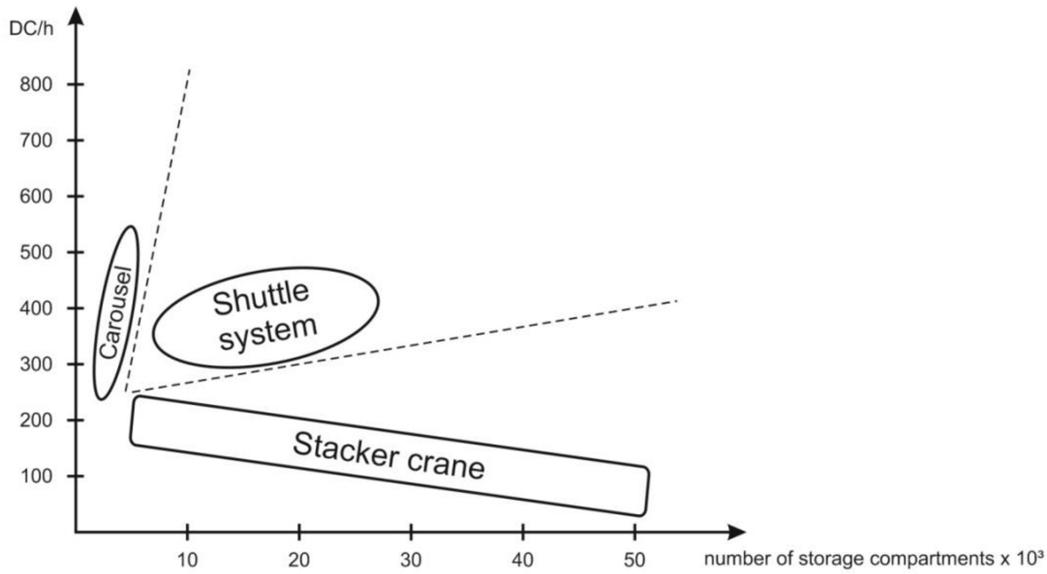


Figure 44: Difference of storage systems regarding double cycles/hour and number of storage compartments[69]

3.3.1 Classification according to net load

A first step to categorize the three automated storage and retrieval systems is to sort them into groups according to the net load of the transported unit loads.

- Class 1: Small load carrier (SLC) with a net load of up to 50kg
- Class 2: Bins or pallets with a net load of up to 2000kg

[69] Modified diagram of content that was elaborated within the effMFS project

It is obvious that the main focus is on Class 1 storage systems, since bin and pallet system do only exist for stacker cranes and partly for shuttle systems. For the desired purpose, Class 1 has to be restricted further since horizontal carousel systems are only capable of storing SLCs with a net load of up to $M_N = 25\ kg$ due to high centrifugal forces and the load limitation of the moving rack system. Since stacker cranes that carry only small load carriers are often also called miniloads, as already outlined in chapter 2.3, this denomination is used further.

3.3.2 Classification according to dimensions

To further narrow down the considered system, another classification has to be introduced. In a first attempt the idea of dividing the AS/RS types into several cubatures came up in the steering committee. The cubatures could be used to define dimensional ranges, in which the relevant storage and retrieval systems are comparable. An example of this concept is depicted in Figure 45.

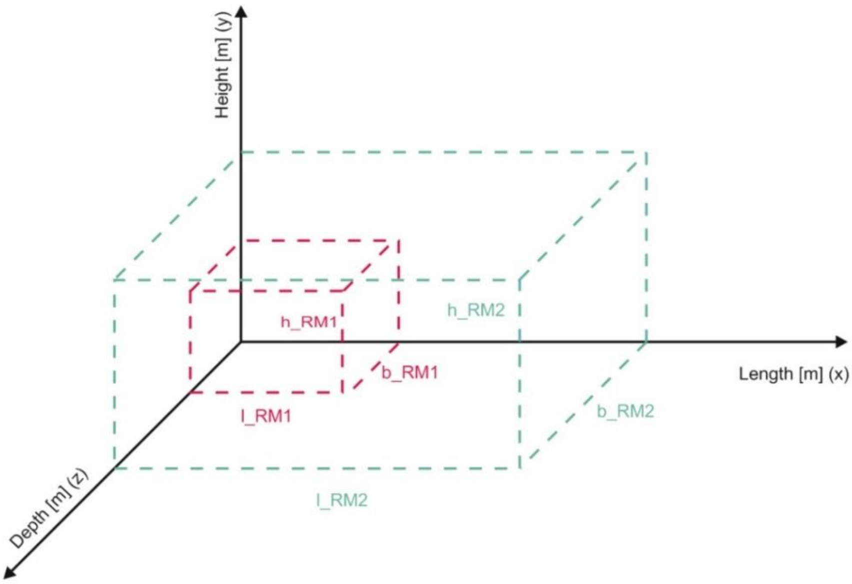


Figure 45: Two exemplary zones when classifying according to a cubature[70]

The desired contrasting is only permissible if the devices that are to be analyzed are within the same cubature which means that each dimension is exactly the same or at least of the same magnitude. One of the greatest advantages of a concept featuring approximately the same dimensions would be, that it simplifies the possibility to transfer the operating cycles and reference points of established standard guidelines like FEM 9.851 or VDI 3561 from miniload to horizontal carousel or shuttle systems. This raises the question which dimensions of the AS/RS can be used to make this classification practical. When considering the maximum of length, height and depth, one has to conclude that there can be a great spread

[70] Modified diagram of content that was elaborated within the effMFS project

of each dimension. This is especially true when contrasting horizontal carousel systems to miniload and shuttle systems, as can be seen in Table 33.

Table 33: Rough overview of the maximum dimensions of each AS/RS

	Miniload system[71]	Horizontal carousel system[72]/ SSI SCS[73]		Shuttle system[74]
h_RM	7-18 m	2,2 – 4,2 m	4,7 – 4,9 m	Up to 12 m
l_RM	Up to 50 m	3,5 – 56 m	Single drive 8,5-18,4 m Double drive: 15,1 – 27 m	Up to 55 m
b_RM[75]	3 – 4 m	1,6 – 2,2 m	10,5 m (Cluster)	2 – 3 m

Of special significance for the desired comparison using standard guidelines are the height h_{RM} and length l_{RM} as already described in the previous chapters. A first attempt to transfer this methodology to horizontal carousel systems is depicted in the following Figures, showing uncoiled racking systems. When considering the rack as stationary and the lift as moving object, which is the opposite of the normal situation, the rack can be regarded as being nearly identical to a miniload. It is possible to apply several use cases defined in FEM 9.851 and VDI 3561. Still there are some differences, like the fact that, the lift can jump from the left to the right and vice versa, since the system is able to rotate in both directions when reaching the edges of the "stationary" rack and that the system still uses the shortest distance to reach the next position.

3.3.2.1 Proposal of VDI 3561-like working cycle for horizontal carousel systems

Figure 46 shows the fictitious VDI 3561 working cycle in an uncoiled horizontal carousel with the starting point on the left (see chapter 2.3.2.4). It has to be mentioned that since the lift is considered as the "moving part", the I/O point is also not stationary and travels with the lift accordingly. Therefore each location of the first rack level has to be considered as I/O point, which leads to an I/O level. Beside this specialty, the position of the reference points as well as the sequence in which they are approached are identical to the guideline. However, since

[71] (Cf. [tJN07], p. 68, 96)

[72] (Cf. [Woh00], p. 66 ; [tJN07], p. 87)

[73] Data provided by SSI Schäfer Peem GmbH, Graz; see also ([Mar11], p. 12)

[74] ([Kna11], p. 4) used as reference, since this system is one of the largest that is currently operated, the biggest system built by Knapp AG for Hugo Boss is currently under construction

[75] B_RM only considered for single device, not the complete cluster; Miniload: only one aisle; Carousel: only one carousel not a cluster; Shuttle: only one aisle

the carousel still is programmed to take the shortest route to the next reference point, the first reference point is not reached by rotating clockwise (lift would move to the right on this map), like it would when following the guideline. It is approached by rotating counter clockwise, because there the distance is only $^1/_3\,L$ (otherwise $^2/_3\,L$). Table 34 lists the coordinates and distances to be covered to reach the reference points.

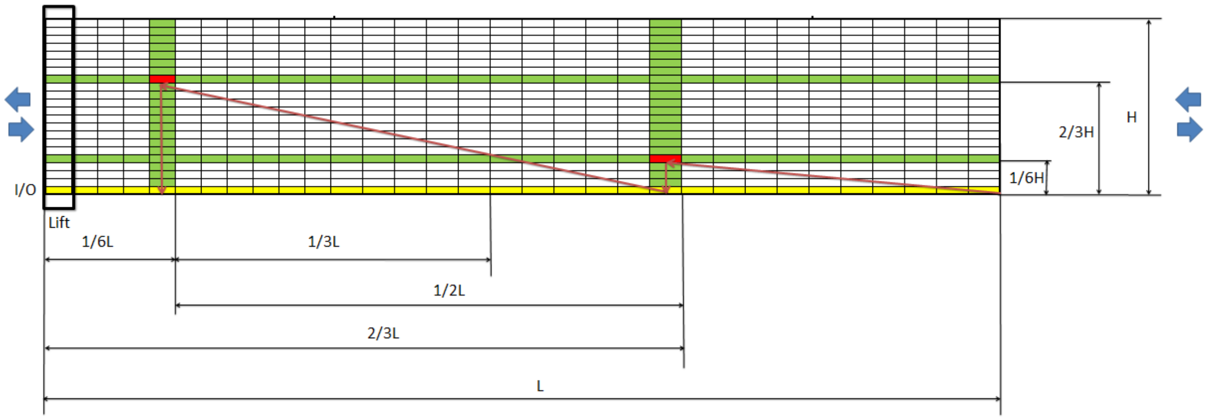


Figure 46: New "VDI 3561" cycle with I/O point on the left in an uncoiled horizontal carousel system

Table 34: Coordinates and distances to travel to the reference points of VDI 3561

	Coordinates	Distance to travel (x-coordinate)	Distance to travel (y-coordinate)
Reference Point P_1	$P_1 = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{6}H \end{pmatrix}$	$^1/_3\,L$	$^1/_6\,H$
Reference Point P_2	$P_2 = \begin{pmatrix} \frac{1}{6}L \\ \frac{2}{3}H \end{pmatrix}$	$^1/_2\,L$	$^2/_3\,H$

The second case that is defined in VDI 3561 features a shifted I/O point with the constraint $L_E \leq {}^1/_2\,L$ (see chapter 2.3.2.4).

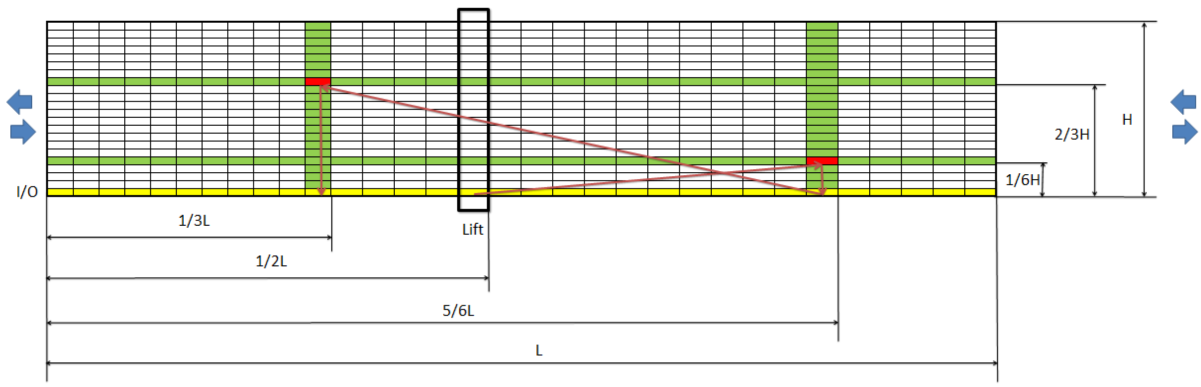


Figure 47: New "VDI 3561" cycle with I/O point in the middle in an uncoiled horizontal carousel system

Again, the position and order of approach of the reference points are according to the guideline. It is worth noting that the distance to be covered between P_1 and P_2 can be accomplished by both rotating clock or counter clockwise, because in both directions it is $^1/_2\,L$. The proposal is depicted in Figure 47. Table 40 lists the coordinates and distances to be covered to reach the reference points.

Table 35: Coordinates and distances to travel to the reference points of VDI 3561

	Coordinates	Distance to travel (x-coordinate)	Distance to travel (y-coordinate)
Reference Point P_1	$P_1 = \begin{pmatrix} \frac{5}{6}L \\ \frac{1}{6}H \end{pmatrix}$	$^1/_3\,L$	$^1/_6\,H$
Reference Point P_2	$P_2 = \begin{pmatrix} \frac{1}{3}L \\ \frac{2}{3}H \end{pmatrix}$	$^1/_2\,L$	$^2/_3\,H$

3.3.2.2 Proposal of FEM 9.851-like working cycle for horizontal carousel systems

The same approach presented before can also be achieved using the FEM 9.851 use cases 1 and 4. Figure 48 shows the uncoiled horizontal system where the first use case is applied. In this scenario the starting point of the lift is on the left side and the first level of the rack is used as I/O level again. The sequence in which the reference points are approached is as well identical to the guideline and is marked with red arrows. Since the distances are smaller, the carousel rotates clockwise. Table 36 lists the coordinates and distances to be covered to reach the reference points.

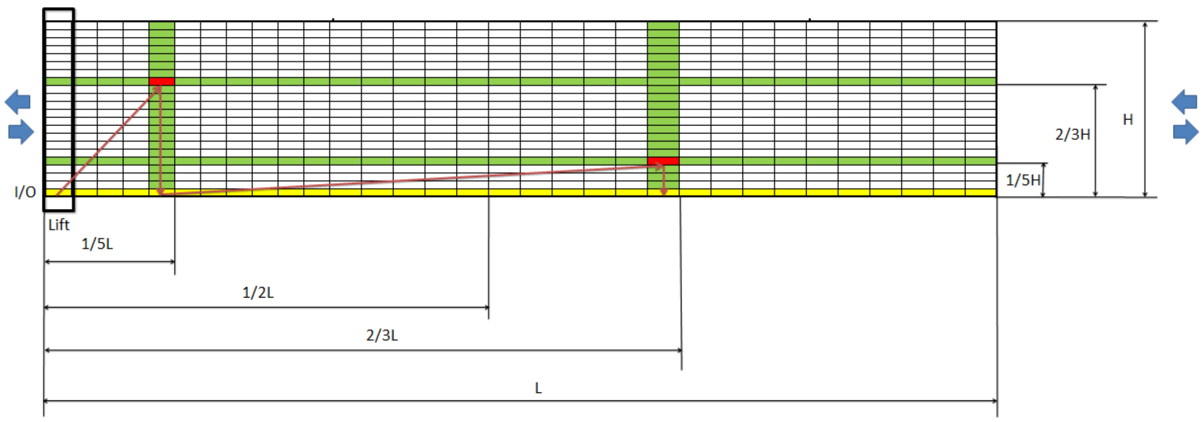


Figure 48: New "FEM 9.851" cycle following use case 1 in an uncoiled horizontal carousel system

When considering FEM 9.851 use case 4, the starting point for the lift is in the middle again. As with all the other presented proposals the position and order of the reference points is identical to the guideline.

Table 36: Coordinates and distances to travel to the reference points of FEM 9.851 use case 1

	Coordinates	Distance to travel (x-coordinate)	Distance to travel (y-coordinate)
Reference Point P_1	$P_1 = \begin{pmatrix} \frac{1}{5}L \\ \frac{2}{3}H \end{pmatrix}$	$^1/_5\,L$	$^2/_3\,H$
Reference Point P_2	$P_2 = \begin{pmatrix} \frac{2}{3}L \\ \frac{1}{5}H \end{pmatrix}$	$^7/_{15}\,L$	$^1/_5\,H$

Figure 49 shows the horizontal carousel system with the procedure for use case 4 whereas the sequence is marked with red arrows.

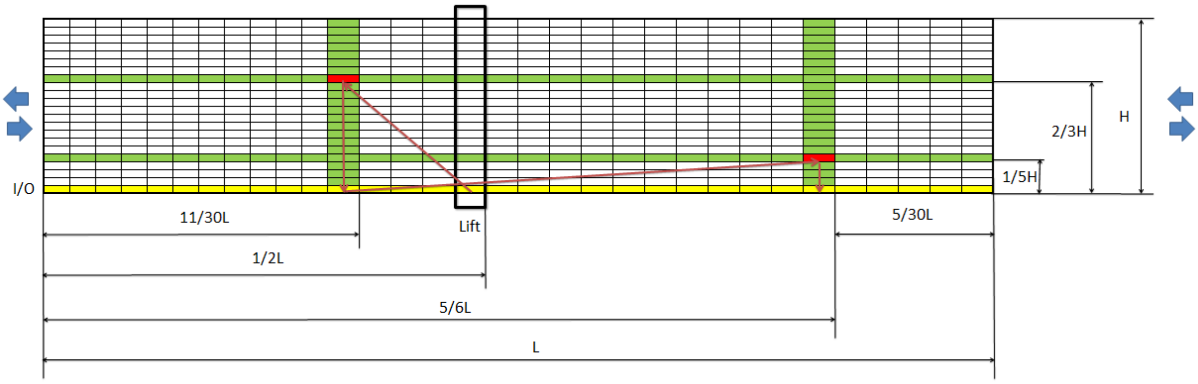


Figure 49: New "FEM 9.851" cycle following use case 4 in an uncoiled horizontal carousel system

Table 37 lists the coordinates and distances to be covered to reach the reference points.

Table 37: Coordinates and distances to travel to the reference points of FEM 9.851 use case 4

	Coordinates	Distance to travel (x-coordinate)	Distance to travel (y-coordinate)
Reference Point P_1	$P_1 = \begin{pmatrix} \frac{11}{30}L \\ \frac{2}{3}H \end{pmatrix}$	$^4/_{30}\,L$	$^2/_3\,H$
Reference Point P_2	$P_2 = \begin{pmatrix} \frac{5}{6}L \\ \frac{1}{5}H \end{pmatrix}$	$^{14}/_{30}\,L$	$^1/_5\,H$

Conclusion about the usability of a classification according to dimensions

Looking at Table 33 to Table 35, it becomes obvious that these ideas are not practical for several reasons. First, the overall dimensions of the fully automatic storage and retrieval systems vary to much in total. The sub-division into several cubatures would help to define several classes but still this methodology has the drawback that is not able to compare every system with every characteristic. The concept excludes any other comparison like comparing differently sized objects. For example, if a warehouse operator would like to compare a new horizontal carousel with the existing old miniload system, with the assumption that both systems do fulfill all desired needs, the systems would possibly not be comparable, simply because the classification is different due to their different dimensions.

The second reason is that even the maximum dimensions are not comparable at all. This is because it is quite common that manufacturers construct their AS/RSs on a modular basis which means that they cluster several devices into larger compounds. This is a good way to either boost the throughput or to raise the number of available storage compartments. Unfortunately, this leads to the fact that the maximum dimensions are not a feasible parameter for any comparison of fully automatic storage and retrieval systems. In general, the only feasible way to provide some kind of comparability is to stripe the cluster down to one single device or aisle.

The third reason is that horizontal carousel systems almost exclusively perform double cycles when traveling to one single storage compartment, because the lift platform is equipped with two storage locations. Hence, when the platform is at the I/O position it grabs the SLC to be stored, travels to the intended storage position, unloads the SLC to be retrieved from the rack into the second platform compartment and finally drops the other SLC into the rack. Since the guidelines emanate from miniload systems two reference points are defined. This means that the working cycle actually is performing two double cycles.

The last reason why this concept has to be withdrawn are the distances a horizontal carousel system would have to travel when using the FEM 9.851 and VDI 3651 approach. In practice these systems are designed to travel ${}^{1}\!/_{10}\,L$ maximum to reach the next position where the storage or retrieval process takes place. Hence the proposed guideline transition does not represent a mean working cycle in a horizontal carousel system. This fact was confirmed by members of the steering committee of the effMFS project and acknowledged by analyzing data from a database of a realized system. The statistics are presented in chapter 3.5.3.3.

3.3.3 Classification according to payload/mass distance

Another parameter that is worth being considered as a basis for comparison can be found in external transport logistics. There the service of moving freight by truck or cargo plane over a specific distance is described in ton-kilometers. Transferred to intralogistics and especially AS/RS this could mean that a more practically relevant parameter is created. Since the distance as only parameter is not usable as shown before, kg- or ton-meters might overcome this problem. It is to deliberate whether the payload of the SLC or the mass of the moving parts of the AS/RS is to be multiplied by the distance. As can be seen in Table 38 quickly, this approach does not lead to the desired outcome since the multiplication of each factor results in values of very different magnitude.

Table 38: Contrasting juxtaposition of distances and masses of all consider AS/RS types

	Mean travelled distance in x-axis	SLC payload	Mass of moving device (rack or SR machine)
Miload system	$^1/_6 - ^1/_2 L$	Up to 50 kg	Up to 10.000 kg
Horizontal carousel system	$^1/_{10} L$	Up to 25 kg	Up to 55.000 kg
Shuttle system	Comparable to miniload	15 – 50 kg	50-100 kg

3.3.4 Classification according to the total capacity

As indicated previously, the number of storage locations is another essential parameter that is the next starting point to find a proper classification. The basic idea is to introduce several classes which provide a clustering that corresponds to the size of the automated storage and retrieval system. A comparison is only done by analyzing storage and retrieval systems within a single class. In a first attempt the total number of storage compartments is used for classification. This is quite self-evidend, since in practice this value is always used as a reference when comparing different systems. A first classification was proposed by the steering committee, which is as follows:

- Class 1: Up to 5.000
- Class 2: 5.001 – 20.000
- Class 3: More than 20.000

As can be seen in Table 39, the total number varies, because again the number of individual devices within a whole cluster can be quite different. Hence, the number of total storage compartments is not the ideal parameter.

Table 39: Rough overview of numbers of storage compartments of each AS/RS type

	Maximum number of storage compartments	Maximum number of storage comparts/device
Miniload system	Up to 110.000[76]	7.200[77]
Horizontal carousel system	Up to 38.000[78]	2.640[79]
Shuttle system	Up to 176.000[80]	5.880[81]

[76] (Cf. [tJN07], p. 68; [TGW11], p. 2)

[77] ([Mec07], p. 5)

[78] ([Kna11], p. 4), Knapp OSR with 21 modules (28 levels); returns-management (Hermes Fulfilment GmbH, Haldensleben)

[79] Data provided by SSI Schäfer Peem GmbH, Graz; one single SCS with 120 carriers and 22 levels

It is necessary to isolate a single device as already proposed. This leads to the following classes in order to classify the systems:

- Class 1: $n_{ges} < 1500$ / device
- Class 2: $1500 \leq n_{ges} < 3000$ / device
- Class 3: $n_{ges} \geq 3000$ / device

Unfortunately, this concept leads to the same problem as before. Even when varying the boundaries of each class, the number of storage compartments per device or aisle can be more than the double when opposing e.g. horizontal carousel systems (2.640 #) to shuttle systems (5.880 #). Since a reasonable classification into classes where all AS/RS types are represented is not possible, this idea has to be withdrawn as well. Again the spread is too large, and does not provide a common base for a solid comparison.

Table 40: Representation of each AS/RS type in the defined classes

	Stacker crane/ Miniload system	Horizontal carousel system	Shuttle system
Class 1	☑	☑	☑
Class 2	☑	☑	☑
Class 3	☑	☒	☑

3.3.5 Limitation of comparison models

During the extensive brainstorming in order to find the appropriate strategy to assess the energy efficiency for different types of storage systems, it became obvious that a comparison is always subject to compromises or limitations. One of the most essential results is the fact, that there are no suitable parameters or combination of the same, which allows a direct comparison of AS/RS of different type and different size at the same time.

To underline this circumstance the approach of ([EG13]; [EG14]) shall be recalled. The reference points used in the representative operating cycle represent the mean cycle time. The energy demand associated with reaching the reference point of course does not represent the mean energy demand of the whole system, but as the author correctly states, this value changes accordingly when varying the dimensions of the rack system and hence the position of the reference point. A simple consideration of the potential, translational and friction energy confirms the correlation, when considering the velocity as constant (which is the case if the reference points for mean cycle times are used, because in this case the distance is long enough to reach the nominal values of v_x and v_y).

[80] ([SSI07], p. 2), SSI Schäfer SCS with 25 carousels (68 carriers, 22 levels); returns-management (Josef Witt GmbH, Weiden)

[81] ([Kna11], p. 4)

Energy demand to reach the position in x-coordinate only:

$$E_x = m_{ASRS} * \frac{v_x^2}{2}$$ Equation 93

Energy demand to reach the position in y-coordinate only:

$$E_y = m_{ASRS} * \frac{v_y^2}{2} + m_{LHD} * g * y$$ Equation 94

As a conclusion it can be said that the larger the rack system gets, the more energy is needed. Additionally, the mean cycle time also increases which means simply that the throughput decreases. Therefore a bigger warehouse is always discriminated when using the energy demand as input variable and the throughput as logistical performance or output variable. The loss of throughput due to higher mean cycle times has to be compensated by another factor like the usable area of the racking system or even better with the travelled distance to the reference point.

Consequently it has to be differentiated between assessments comparing the same or different AS/RS types as it is depicted in Figure 50.

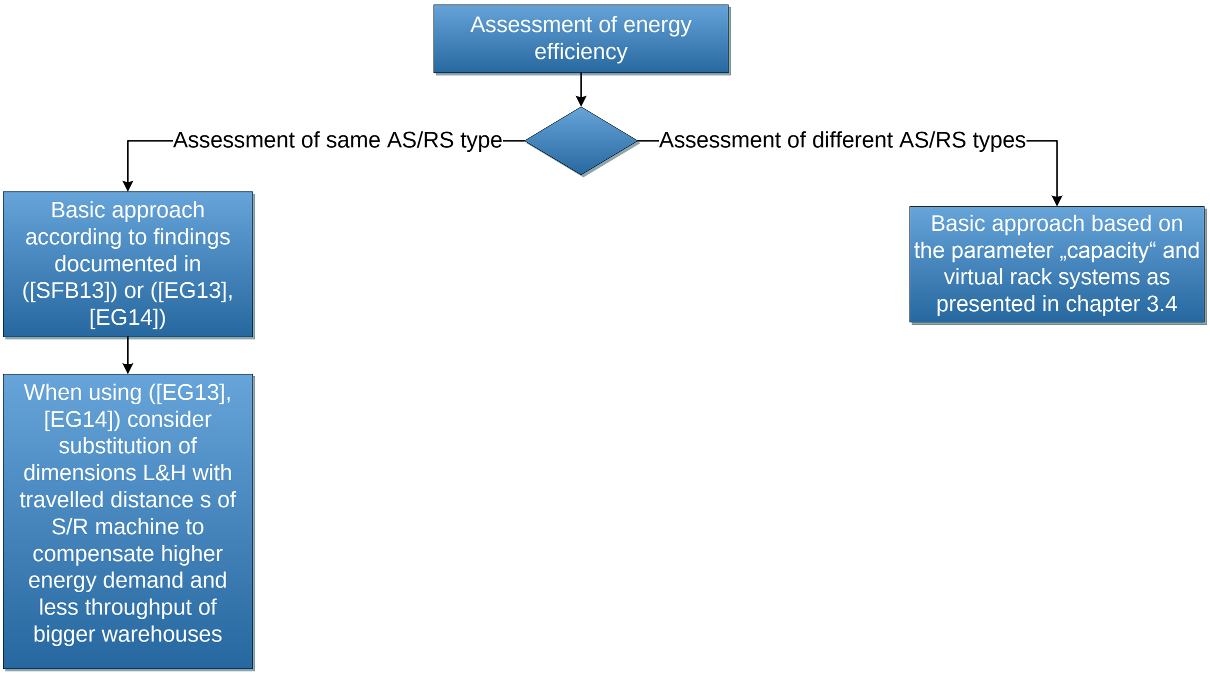


Figure 50: Necessary distinction when assessing the energy efficiency of AS/RS

3.4 Establishment of equivalency by introducing a new approach

In the following chapter a methodology is described in theory, which puts miniload, horizontal carousel and shuttle system on an equal footing. This approach is designed to overcome the distinctive features of each system and is the first step to provide a simple comparison of the energy demand of the automated storage and retrieval systems.

The parameter capacity, that was already touched in chapter 3.3.4, seems to be the most promising parameter, since it is essential for all three types of AS/RS and hence can serve as a basis for the new approach. In general, the attempt to use the number of storage locations for classification is not to be given up, but it becomes particularly obvious that a definition has to be found that maps a horizontal carousel into a miniload system and not vice versa as it was attempted in the previous chapters.

Based on the fact that the capacity is a parameter that is determined based upon the desired needs of the system's future operator, this procedure seems to be an ideal starting point. Hence, the first step is to define the number of storage compartments with regards to the user's needs. This also includes the definition of the size of the small load carries, that are to be stored, as a pre-condition.

Since the demand-oriented capacity has to be identical for all systems, some systems have to be adopted to fit to the defined parameter. Very likely the horizontal carousel systems are the smallest fully automatic systems in such a comparison, hence, the number of storage compartments has to be transferred to miniload systems and shuttle systems. This approach further suggests to calculate equivalent rack dimensions for these systems. In the course of a reverse-engineering approach, the dimensions h_{RM} and l_{RM} of a virtual racking system are calculated. Since the racking system of miniload and shuttle systems share many similarities it is a comparably small effort to close the missing gap. An overview of the process is depicted in Figure 51.

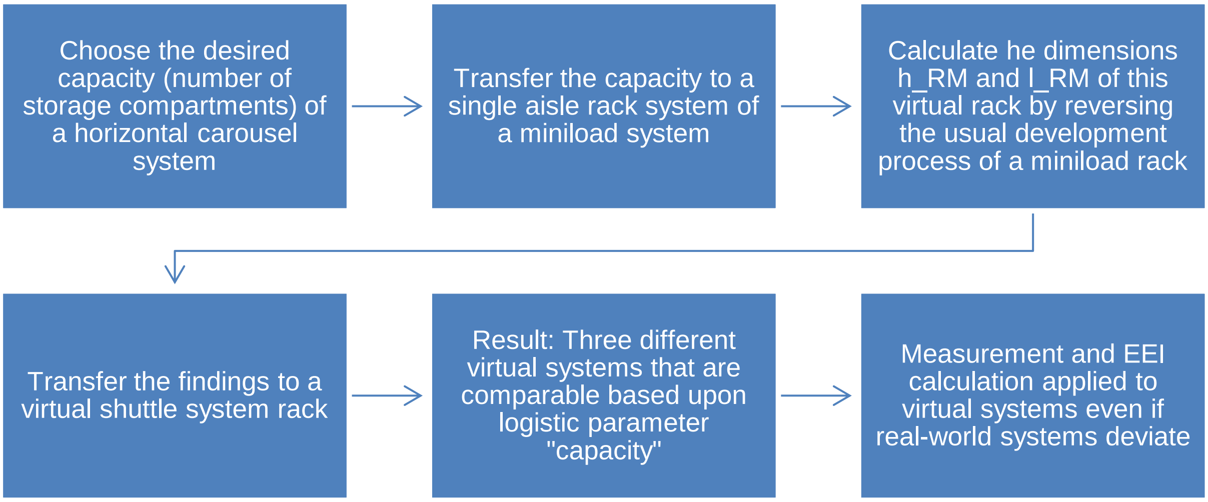


Figure 51: Schematic diagram of process to establish equivalency of AS/RS types

The measurements are then performed using the virtual rack systems, which are mapped into the real rack systems. This has the advantage that even if the real rack systems of the miniload or shuttle system are not equal to the horizontal carousel system in terms of dimensions, a comparison is still possible due to the same capacity.

The reference points are now positioned in such way that the cycle on its own represents a realistic mean working cycle as it can be found in practice. Thereby the function storing or retrieving becomes even more focused. The representative operating cycle is defined and presented in chapter 3.5.3.

3.4.1 Dimensioning of virtual racks

While horizontal carousel systems use a special dynamic rack system, miniload and shuttle systems are designed to have a static rack and therefore are usually constructed using an ordinary shelf rack store.

The shelf rack store consists of so called place modules that reside within the rack construction. The place module contain either only a single or several storage compartments. The place modules are arranged similar to a honeycomb on both sides of the aisle. One aisle and two adjacent storage modules form an aisle module. ([GK12], p. 462) The total dimensions of the shelf rack store, are defined by the total number of parallel aisle modules, resulting in the already mentioned cluster.

The calculation scheme that results in the dimensions of such a shelf rack store is a bottom-up process as can be seen in Figure 52. The dimensions of the small load carrier, which are depicted in Figure 53 are the starting point. The length of the storage place is dependent on the number of storage compartments, the length of a SLC and the shelf clearance in x-coordinate. When put together a place module can be formed and assembled arbitrarily.

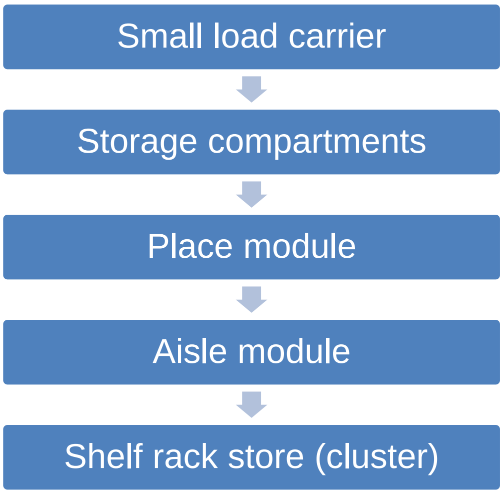


Figure 52: Process to calculate dimensions and capacity of a shelf rack store

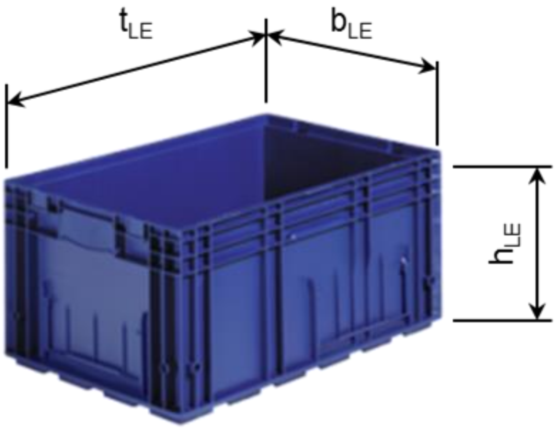


Figure 53: Dimensions of the small load carrier

The rack shelf depth depends on the number of SLCs to be stored behind each other. As already mentioned, the depth is usually single or double deep. Since the definition of the width here is only single deep (which is sufficient), the calculation simply adds the shelf clearance in z-coordinate. The height is defined by the SLCs height plus the shelf clearance in y-coordinate. Figure 54 features an overview of all dimensions.

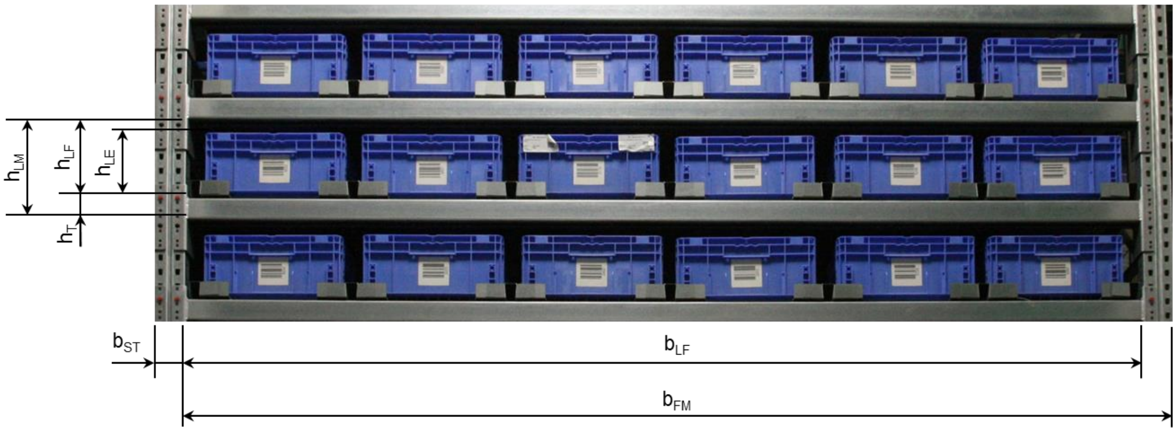


Figure 54: Dimensions of storage compartment and place module of a shelf rack

Formulas to calculate the dimensions of a storage place:

$$b_{LF} = c_{LP} * b_{LE} + (c_{LP} + 1) * b_C$$ Equation 95

$$h_{LF} = h_{LE} + h_C$$ Equation 96

$$t_{LF} = t_{LE} + t_C$$ Equation 97

By adding the width and height of a shelf rail, the dimensions of a place module can be calculated in the following way:

$$b_{FM} = b_{LF} + b_{ST}$$ Equation 98

$$t_{FM} = t_{LF}$$ Equation 99

$$h_{FM} = h_{LF} + h_T$$ Equation 100

The dimensions of a whole aisle module are calculated by multiplying the number of place modules with the dimension in both directions, horizontally and vertically. Further the dimension of a shelf rail and the lower shelf clearance is added. The latter is necessary for the S/R machine to approach the lowest level of the rack. The total width of an aisle is formed by adding the depth of two racks together with the width of the aisle.

Formulas to calculate the dimensions of an aisle module:

$$l_{RM} = n_H * b_{FM} + b_{ST}$$ Equation 101

$$b_{RM} = 2 * t_{FM} + A_{ST}$$ Equation 102

$$h_{RM} = n_V * h_{FM} + UAM$$ Equation 103

Table 41: Nomenclature of calculation scheme to determine the rack dimensions

Nomenclature	
$\boldsymbol{b_{LE}}$	Length of SLC
$\boldsymbol{h_{LE}}$	Height of SLC
$\boldsymbol{t_{LE}}$	Depth of SLC

b_{LF}	Length of storage place
h_{LF}	Height of storage place
t_{LF}	Depth of storage place
c_{LP}	Number of storage compartments within a single place module
b_C	Shelf clearance in x-coordinate
h_C	Shelf clearance in y-coordinate
t_C	Shelf clearance in z-coordinate
b_{FM}	Length of place module
h_{FM}	Height of place module
t_{FM}	Depth of place module
b_{ST}	Width of a vertical shelf rail
h_T	Height of a horizontal shelf rail
l_{RM}	Length of aisle module
h_{RM}	Height of aisle module
b_{RM}	Depth of aisle module
n_H	Number of place modules in horizontal direction (x-coordinate)
n_V	Number of place modules in vertical direction, equals number of levels (y-coordinate)
A_{ST}	Width of aisle
UAM	Lower shelf clearance

In Figure 55 the calculated dimensions of the aisle module are depicted accordingly.

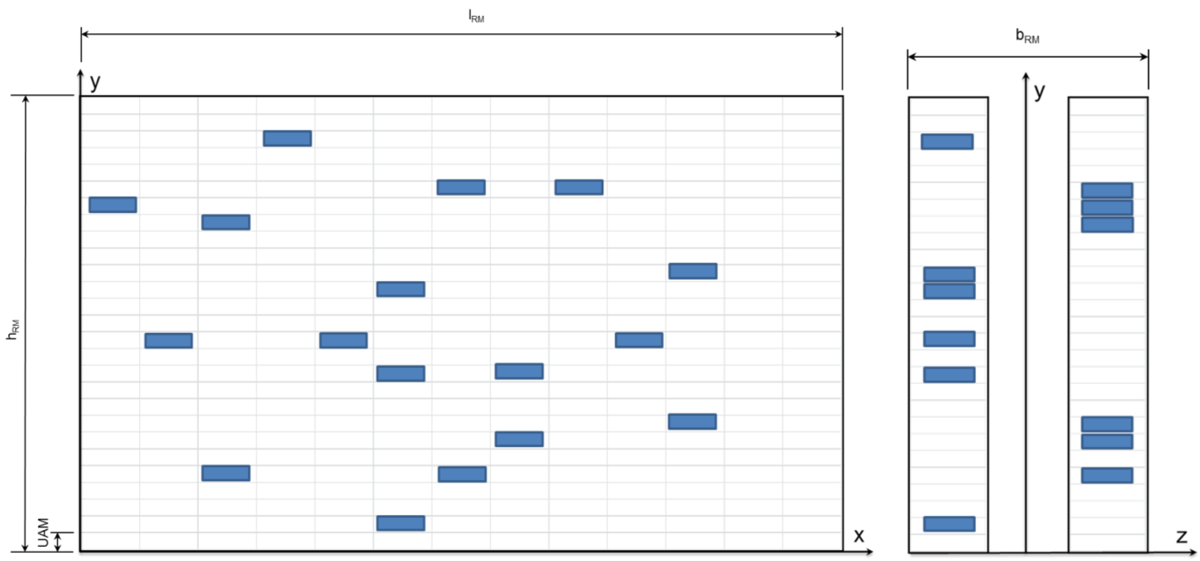


Figure 55: Total dimensions of a single aisle module

To simplify and expedite the calculation process, a VBA script was programmed for MS Excel that automatically determines the desired dimensions. Some initial parameters can be chosen as desired, while essential factors like velocity, acceleration or clearance levels are selected out of a database[82] that contains values which are taken from real-world examples. Based upon the right shelf unit parameter the integrated solver then determines h_{RM} and length l_{RM}, as well as the location of the reference points of a miniload system.

3.5 Energy efficiency indicator (EEI) models

3.5.1 Pre-conditions of EEIs models

Indicators, also called basic or characteristic numbers, are basically used to quantify and evaluate a significant actual situation. An indicator consists of a measure as well as a corresponding unit and is derived by aggregation of measurements, a mathematical description or a contrasting assessment. Indicators are an easy way to visualize and objectify actual situations and their results. (Cf. [tH11], p. 147; [SFB13b], p. 199)

In general indicators can be sub-divided into two types:

- Absolute indicators: can be measured directly at a test bench, and are embodied in this thesis by the power and energy demand
- Relative indicators: the quintessence is derived by juxtaposing the absolute indicator to a reference value, which is embodied in thesis by the so called logistical performance

As already stated in the first chapter the definition of such a reference value is not trivial since it has to combine the opposing characteristics of all AS/RS types and represent the real benefit that has been achieved by the absorbed energy. The definition of such reference values is described in the following chapters.

3.5.2 Criteria for EEIs models

3.5.2.1 Rated values

The rated or nominal values that are needed throughout the energy efficiency classification process and for calculation purposes arise directly from the already described establishment of equivalency or have already been defined.

- Absolut dimensions of small load carrier b_{LE} and h_{LE}
- Nominal payload M_N

3.5.2.2 Measured values

The following value has to be determined by experimental measurement:

---

[82] (Based upon work in [Pic10])

- Electrical demand measurement of the complete AS/RS system at the defined point of measurement according to the defined system boundaries

Depending on the actual load spectrum the following operating factors have to be varied:

- Load condition (portion of payload) M_i
- Time interval T_i

3.5.3 Representative operation cycle

To determine and measure the electrical power and energy demand respectively, a representative operation cycle (ROC) is provided. The ROC represents a typical standard working cycle of an automated storage and retrieval system. Per definition the ROC consists of several operating states that include the specific load spectrum and the correlating period of time within which the loading is applied to the system.

3.5.3.1 Load spectrum

In a first thought, it was intended to include single cycles, double cycles and relocations of small load carrier into the load spectrum. Since the rack system is already restricted to single deep storage locations, a relocation process is not necessary any longer. Furthermore, as already outlined in chapter 2.2.3, the relocation is never performed on a daily basis, since that would only lead to losses in throughput. Further, the steering committee decided to withdraw single cycle operation due to the fact, that all industrial manufacturers are trying to perform as little single cycle operations as possible to avoid empty or unloaded driving.

Since the load spectrum is only defined for a dual command or double cycle operation, it consists of the following three phases:

- Full load
- Partial load
- Standby

The total amount of time used for all recommended operating states sum up to $T_N = 1\,h$. Each period is a percentage of T_N and can be calculated according to

$$T_i = t_i * T_N \qquad \text{Equation 104}$$

Table 42: Nomenclature of time calculation scheme

Nomenclature	
$\boldsymbol{T_i}$	Time slice of operating state [h]
$\boldsymbol{t_i}$	Percentage [%]
$\boldsymbol{T_N}$	Total time of measurement

Table 43 lists the coefficients which define each single operating state of the load spectrum that is contained in the representative operating cycle.

Table 43: Coefficients for each operating state of the ROC

i	Operating state	Percentage of payload m_i	Percentage of time period t_i
1	**Full load**	90%	20%
2	**Partial load**	50%	60%
3	**Standby**	0%	20%

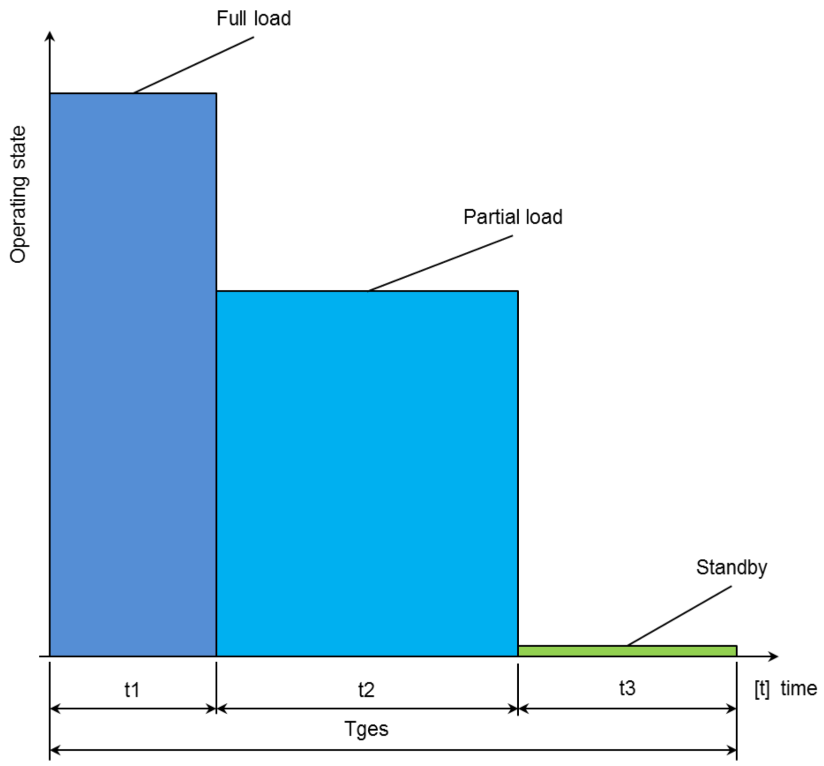


Figure 56: Graphical visualization of the ROC

Beside measuring the partial power demand P_i of each operating state, the amount of small load carriers that are stored or retrieved within the time period has to be counted. This is vital to calculate the throughput Λ_i. Alternatively the throughput can also be calculated by dividing the time period by the cycle time. The different payloads within in the load spectrum are defined via the relative loading m_i, which is a percentage of the nominal load of $M_N = 25kg$.

3.5.3.2 ROC in miniload systems

The representative operating cycle shall be defined for normal single-aisle miniload systems. Curve-traversing systems are not considered in this thesis.

The reference point are calculated according to the derivation that is used in VDI 3561 and FEM 9.851. The formula or the suitable use case respectively shall be used to calculate the reference points by using the dimensions l_{RM} and h_{RM} of the virtual miniload rack system. If the real-world miniload rack is of different size, the ROC is performed within the dimensions of the virtual rack, hence, the absolute positions stay the same.

As shown in Chapter 2.3.2.2, the expected value of the cycle time for a double cycle is defined as:

$$E(t_l)_{ij} = \frac{1}{(l_{RM} h_{RM})^2} * \int_0^{h_{RM}} \int_0^{h_{RM}} \int_0^{l_{RM}} \int_0^{l_{RM}} Max[\left(\frac{|x-x'|}{v_x} + \frac{v_x}{a_x}\right); \left(\frac{|y-y'|}{v_x} + \frac{v_y}{a_y}\right)] dx dx' dy dy' \quad \text{Equation 105}$$

If the shelf unit parameter is $w \neq 1$ the integral has to be solved exactly in order to find the positions of the reference points. Otherwise one can also follow the approach of VDI 3561 and FEM 9.851 by setting the acceptable range to $0{,}5 < w < 2$ and live with deviant values for the cycle time. With the shelf unit parameter $w = 1$, the integral can be solved and together with the geometric interpretation of the formula the well-known reference points with a distance of $\frac{14}{30}x$ and $\frac{14}{30}y$ on the isochrones are defined.

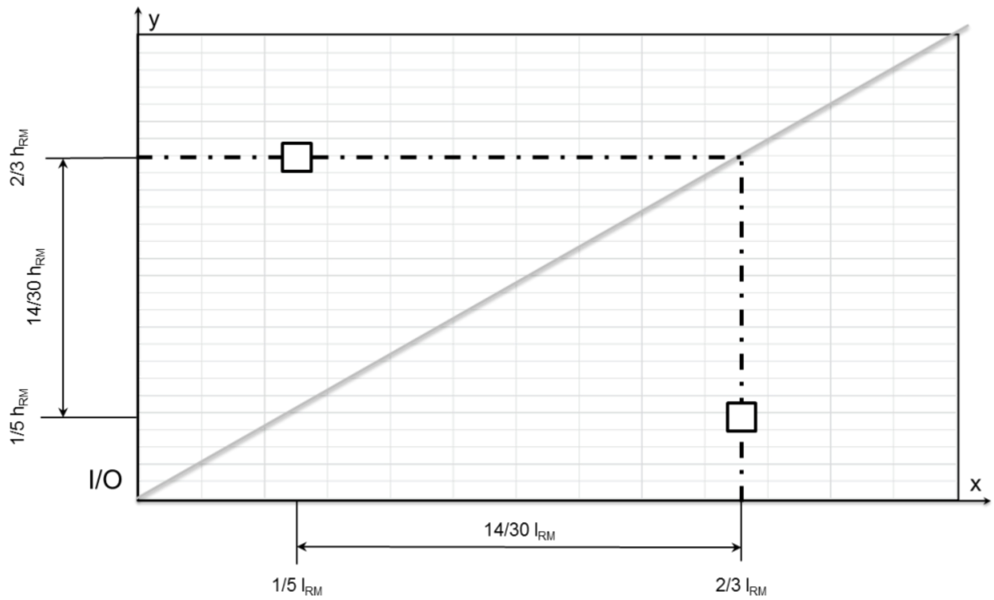


Figure 57: Reference points for dual command cycle in a miniload system

Exemplarily, the positions for use case 1 of FEM 9.851 and VDI 3561 are mentioned again. The only difference between FEM 9.851 and VDI 3561 is the simplification of $\frac{14}{30} \approx \frac{1}{2}$.

Table 44: Coordinates and distances for ROC according to FEM 9.851 use case 1

	Coordinates	Distance to travel (x-coordinate)	Distance to travel (y-coordinate)
Reference Point P_1	$P_1 = \begin{pmatrix} \frac{1}{5} l_{RM} \\ \frac{2}{3} h_{RM} \end{pmatrix}$	${}^{1}/_{5}\, l_{RM}$	${}^{2}/_{3}\, h_{RM}$
Reference Point P_2	$P_2 = \begin{pmatrix} \frac{2}{3} l_{RM} \\ \frac{1}{5} h_{RM} \end{pmatrix}$	${}^{14}/_{30}\, l_{RM}$	${}^{14}/_{30}\, h_{RM}$

Table 45: Coordinates and distances for ROC according to VDI 3561 use case 1

	Coordinates	Distance to travel (x-coordinate)	Distance to travel (y-coordinate)
Reference Point P_1	$P_1 = \begin{pmatrix} \frac{2}{3} l_{RM} \\ \frac{1}{6} h_{RM} \end{pmatrix}$	${}^{2}/_{3}\, l_{RM}$	${}^{1}/_{6}\, h_{RM}$
Reference Point P_2	$P_2 = \begin{pmatrix} \frac{1}{6} l_{RM} \\ \frac{2}{3} h_{RM} \end{pmatrix}$	${}^{1}/_{2}\, l_{RM}$	${}^{1}/_{2}\, h_{RM}$

3.5.3.3 ROC in horizontal carousel systems

As already mentioned in chapter 3.3.2.1 and 3.3.2.2, the definition of reference points is not possible by simply transferring the FEM 9.851 and VDI 3651 approaches to horizontal carousel systems. Therefore the positions were determined by analyzing real-world live data that was acquired from database queries of customer installations. The data was provided by SSI Schäfer Peem Graz and features two applications from a South American customer. The first application is used for picking hence, the horizontal carousel system (called Schäfer Carousel System – SCS) always performs double cycles. Furthermore the database log also contains the payload of the SCS that is stored or retrieved. The second application is used as a shipping warehouse which means that most of the time single cycles are performed. Unfortunately this data does not provide any information about the mass of the bins. Both application share the same type of construction. The SCS features 64 carriers with 15 levels.[83]

Table 46: General information about database log

Picking Carousel		Shipping Carousel	
Operating Cycle	Dual command	**Operating Cycle**	Single command
Nr. of S/R operations (turns)	1223	**Nr. of S/R operations (turns)**	2098
Observation period	21h 33min 40s	**Observation period**	12h 47min 50s
Initial position	x2/y5	**Initial position**	x32/y9

Life data of Picking Application:

The provided spreadsheet contains the time, the position of the storage compartment in the form of the x- and y-coordinates as well as the payload. An excerpt is shown in Table 47.

[83] Due to constructive limitations level 1 is not in use

Table 47: Excerpt of life data from an SSI SCS horizontal carousel system for a picking application

22-23:47:10.437	x-coord:	2	y-coord:	5	weight:	2087
22-23:49:55.672	x-coord:	4	y-coord:	5	weight:	1503
22-23:50:04.002	x-coord:	4	y-coord:	3	weight:	2199
22-23:50:13.882	x-coord:	4	y-coord:	15	weight:	5411
…	…	…	…	…	…	…

In order to define a representative operating cycle, it is of particular interest to know the mean number of position that a horizontal carousel system moves along the x- and y- axis. Therefore several VBA modules were coded in MS Excel that automatically determine statistical values out of the raw data. The Figures depicting the logic behind the code using the unified modeling language can be found in the addendum.

Module 1, is used to determine the movement along the x-coordinate. It executes the following:

- Calculation of the difference between each carrier position from order to order[84]
- Calculation of the mean, max and min of the difference either dependent on or independent of the turn direction
- Determination of the turn direction (left, right, none, indifferent) and correction of the turn directions of the carousel, if applicable[85]
- Number and frequency of approaches for each carrier

Findings:

The following insights could be made:

Table 48: Findings of module 1 of the picking application

Minimum carrier number	1
Maximum carrier number	44
Turns to the right	461
Turns to the left	453
No turns	305
Turn direction not clear (indifferent)	4
Mean travel distance of carousel in x-coordinate[86]	5,433 positions

[84] The difference resembles the number of positions that the carousel travels between two different orders

[85] The turn direction is reversed if the difference is greater than half of the total numbers of carriers (shorter distance)

[86] If the turn direction is not taken into consideration

Figure 58 shows the frequency in which each carrier is approached by the S/R machine. The number that is plotted on the x-axis of the diagram is the actual number of the carrier. It can be noticed that not all carriers were used within the observation period which is due to the fact that horizontal carousel systems are programmed to move as little as possible due to the high net loading.

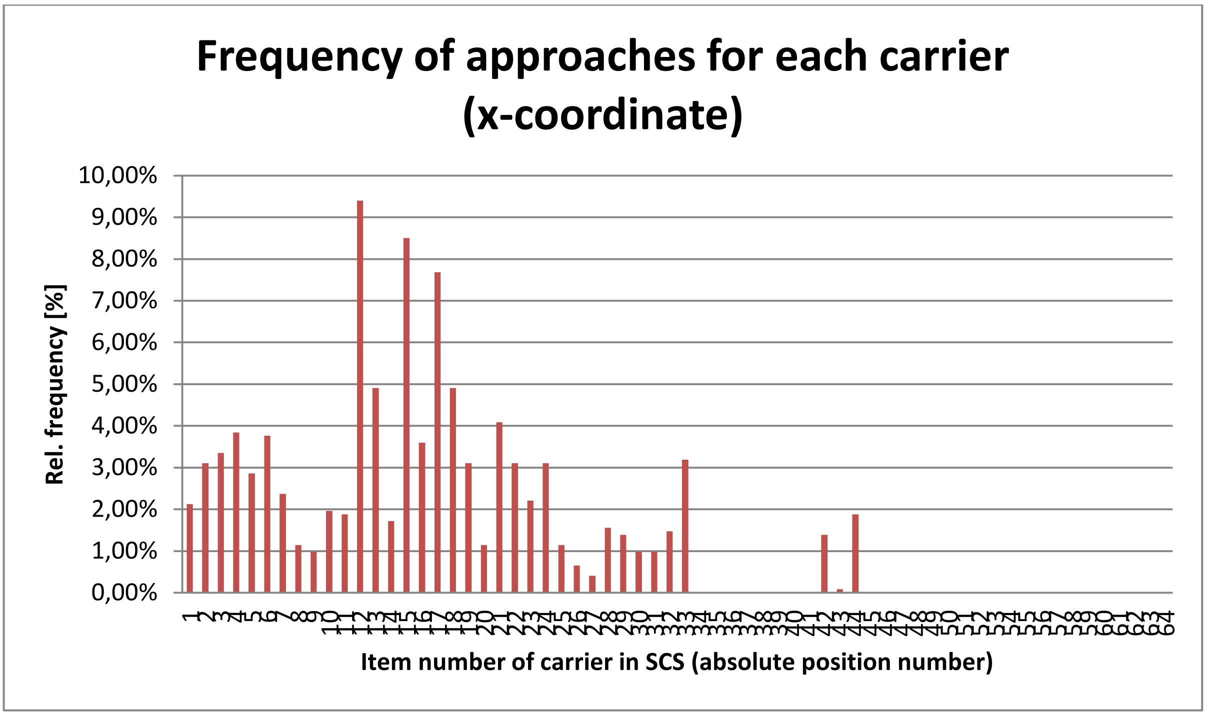


Figure 58: Frequency of approaches for each carrier (x-coordinate)

Figure 59 shows the number of positions in x-coordinate that the carousel travels between two different DC cycles. In contrast to Figure 58 the numbers that are plotted on the x-axis are relative numbers that represent only the difference between each carrier. Further the data behind the diagram does not take the turn direction into consideration. Looking at Figure 60, one can see the same data, but with a distinction between movement to the left (negative sign) and to the right (positive sign). One can also see that the distribution of the movement is bell-shaped, which underlines the fact, that in general only little movements are executed.

The findings further prove what was already communicated by representatives of the company SSI Schäfer-Peem. In average, a horizontal carousel system travels 5 – 6 positions between two storage and retrieval orders (two double cycles). In German this is also called “Suchtiefe” and expresses the maximum range (number of positions) in which the item for the next order is to be found and retrieved in average. Since the structure of customer orders is not predictable and different at any time, the control system pre-sorts the articles in order to ensure that the next order can be completed within the number of positions defined by the “Suchtiefe”.

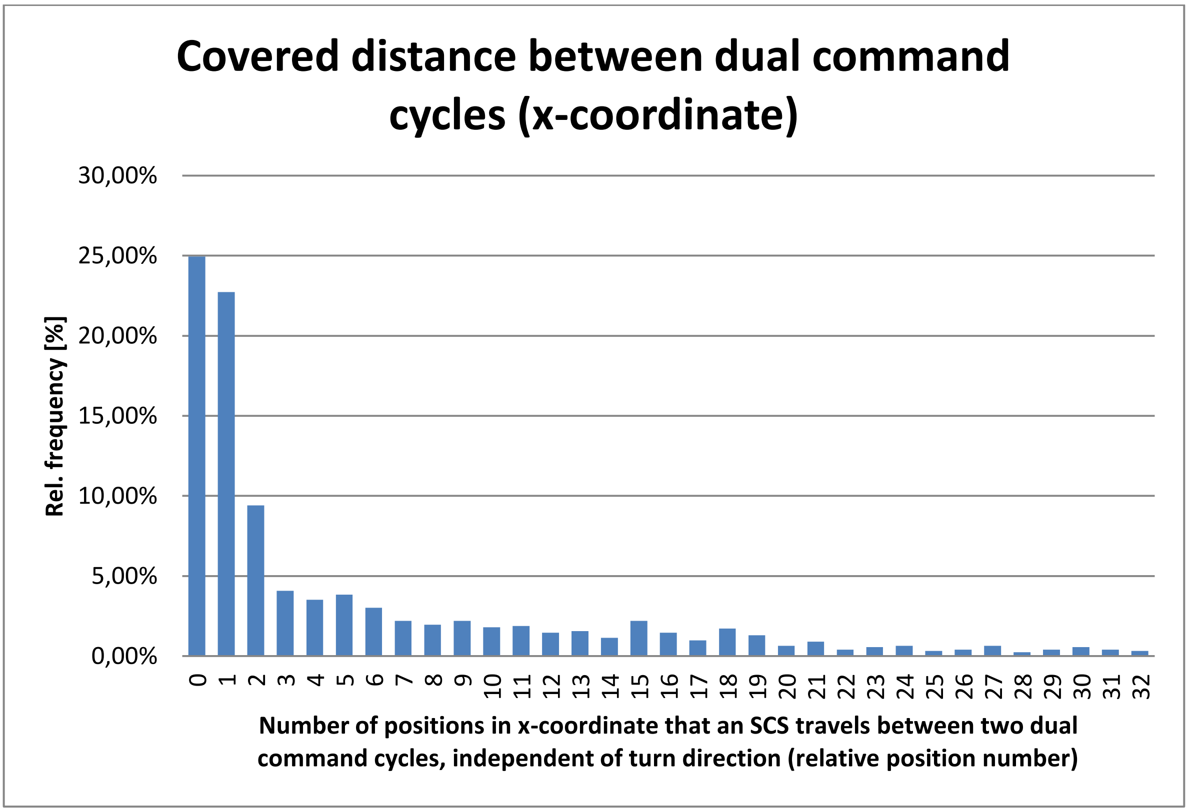


Figure 59: Distance covered by carousel between two double cycles, independent of turn direction

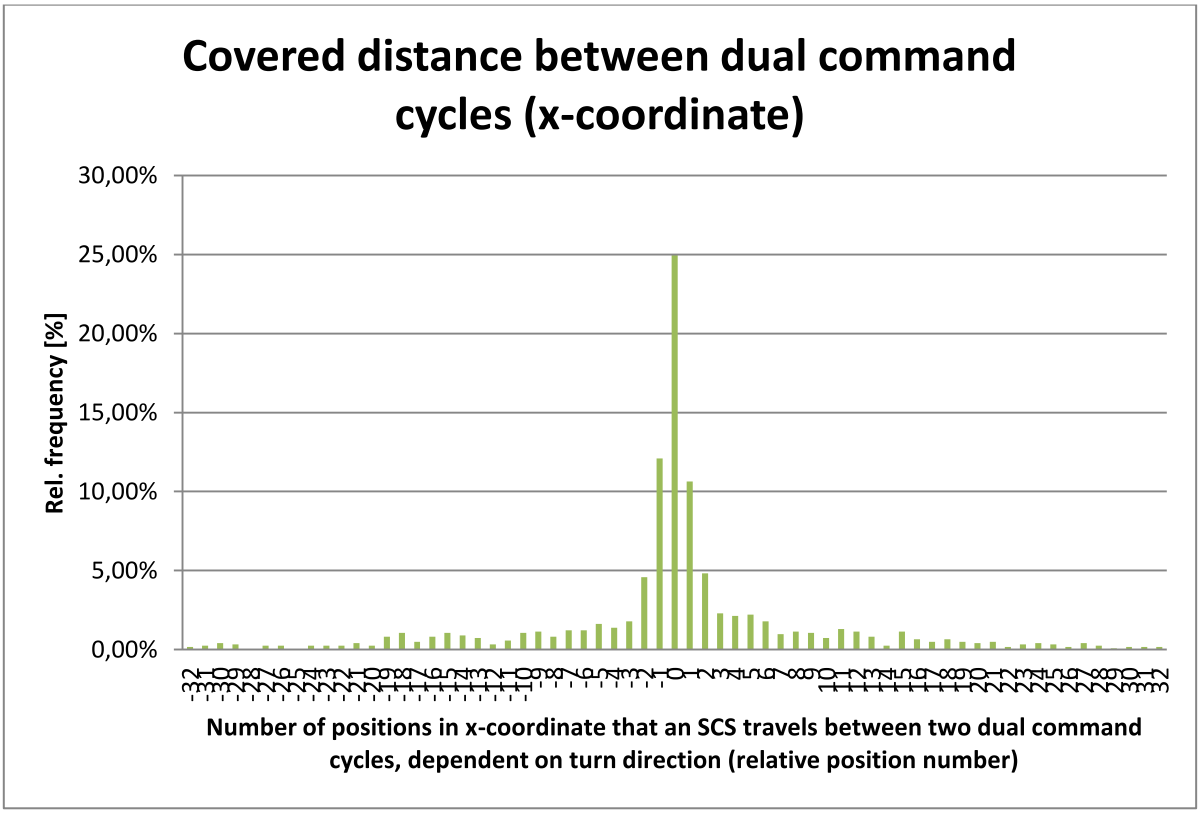


Figure 60: Distance covered by carousel between two double cycles, dependent on turn direction

Module 2 is used to determine the movement along the y-coordinate. It executes the following:

- Calculation of the difference between each level from order to order[87]
- Calculation of the mean, max and min of the difference
- Determination of upward or downward movement
- Number and frequency of approaches for each level

Findings:

The following insights could be made:

Table 49: Findings of module 2 of the picking application

Minimum level number	2
Maximum level number	15
Upward movements	543
Downward movements	453
No movement	71
Mean travel distance of lift in y-coordinate	4,403

Figure 61 shows the frequency in which each level is approached by the S/R machine. The number that is plotted on the x-axis of the diagram is the actual number of the storage level. As can be seen easily, that level number one was never approached, which is due to structural conditions. The I/O point is located at level number three.

Figure 62 shows the number of positions in y-coordinate that the lift travels between two different DC cycles. In contrast to Figure 61 the numbers that are plotted on the x-axis are relative numbers that represent only the difference that was covered and not the number of the level itself.

Further, the data behind the diagram does not take the direction of movement (up- or downward) into consideration.

[87] The difference resembles the number of positions that the lift travels between two different orders

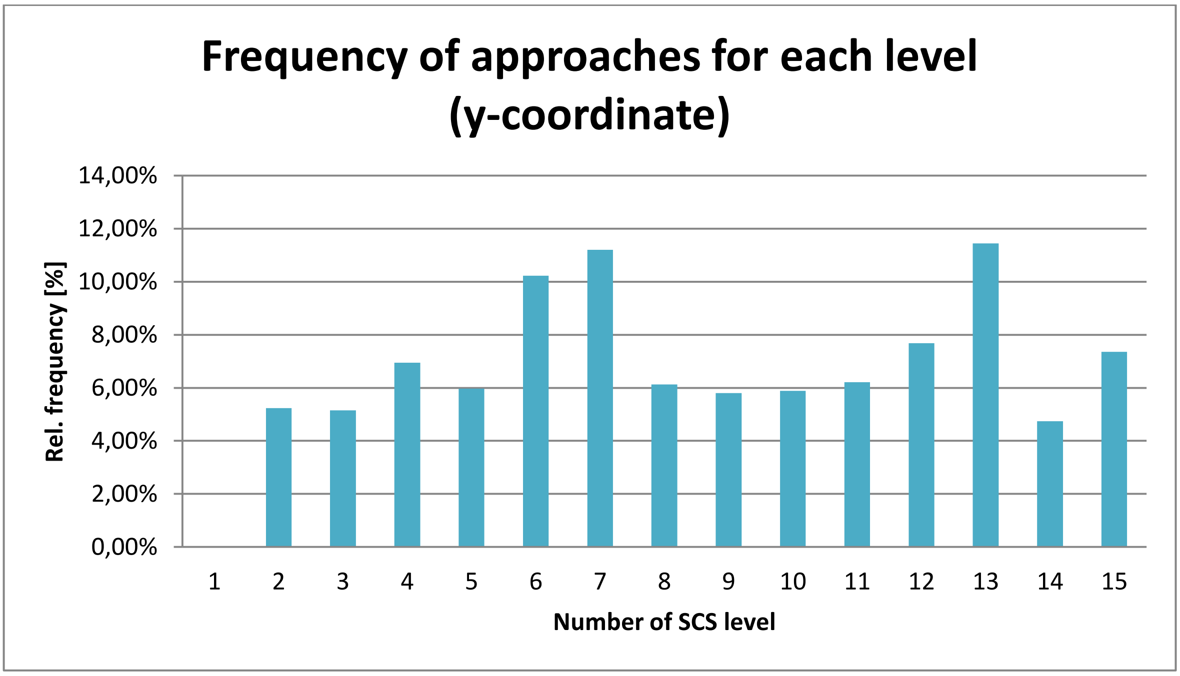


Figure 61: Frequency of approaches for each level (y-coordinate)

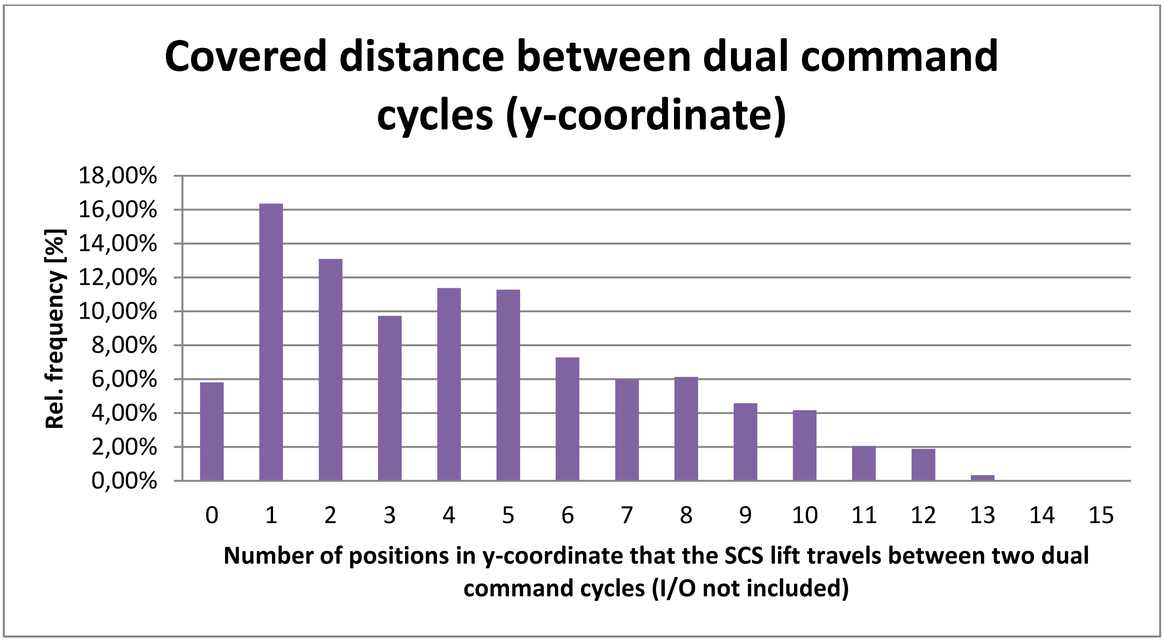


Figure 62: Distance covered by lift between two double cycles, independent of direction of movement

Looking at Figure 63, one can see the same data but with a distinction between upward (negative sign) and downward movement (negative sign). Again the curve is bell-shaped. In average the lift of a horizontal carousel system travels 4 –5 positions between two storage and retrieval orders (two double cycles). This number does not include the number of positions that have to be travelled to the I/O point and back and thus only represents the difference between two storage compartments.

Module 3 is used to determine the movement along both the x and the y-coordinate at the same time.

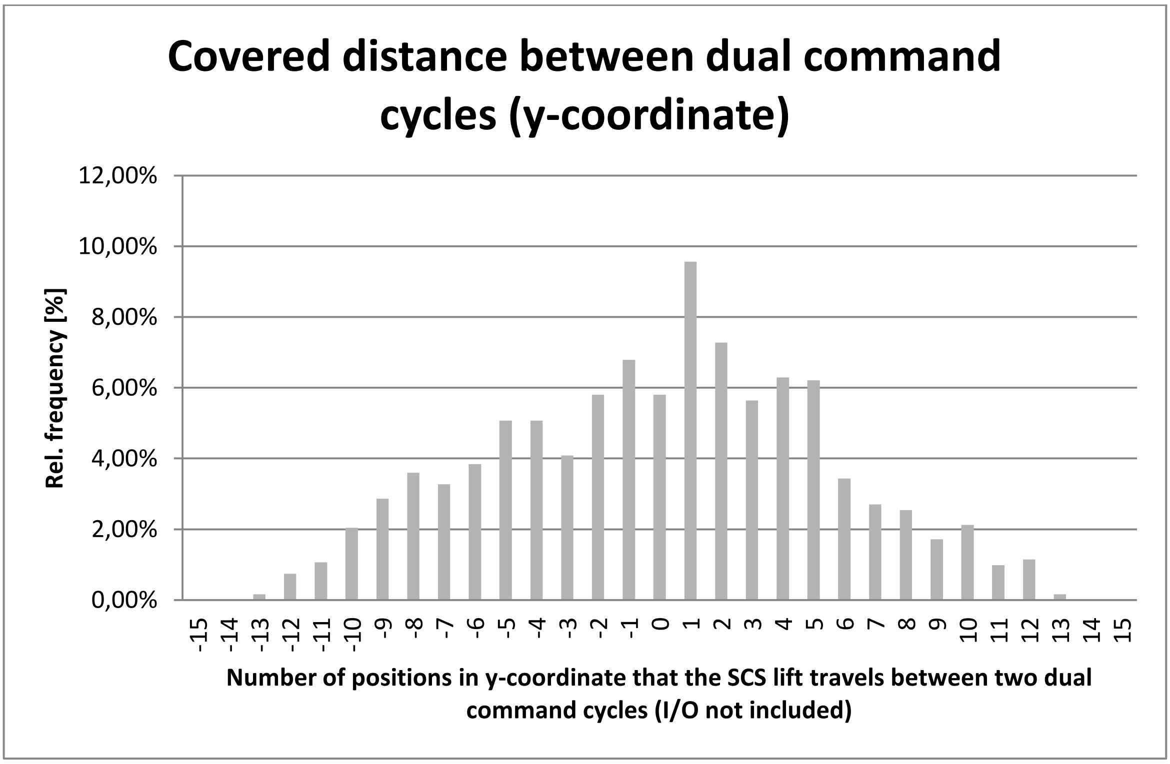


Figure 63: Distance covered by lift between two double cycles, dependent on direction of movement

It determines if the previous and the next storage position differ and writes the answers “yes” or “no” into the specified column. The module does not take the ride from and to the I/O position into account, it simply checks if there is a difference in the position number of the storage compartments in x- and y-coordinate.

Module 4 is used to determine the total length of the track that the lift travels. It therefore calculates the difference of positions between the current position and the I/O point, as well as the difference between the I/O and the next compartment and simply adds up the numbers. Assuming that each storage compartment is 266,67 mm high (4m usable carrier height divided by 15 levels), the total track can be calculated accordingly.

Findings:

The following insights could be made:

Table 50: Findings of module 4 of the picking application

All movements include approach of I/O point at level 3	
Minimum travel distance of lift in y-coordinate	0 positions
Maximum travel distance of lift in y-coordinate	24 positions
Mean travel distance of lift in y-coordinate	11,597 positions
Minimum track	0 mm
Maximum track	6400 mm
Mean track	3092,505 mm

Module 5, 6 and 7 basically perform the same task. All modules can be used to categorize the payload of the SLCs that was logged in the database and to assign it to predefined groups. Module 5 analyses each of the 1223 entries whereas module 6 and 7 are free of payload duplicates that are contained within these entries (only 976 entries). The script simply compares the value of the actual cell with a given range (e.g. 0-500g) and thus assigns it to a numbered group. The result is shown in Figure 64.

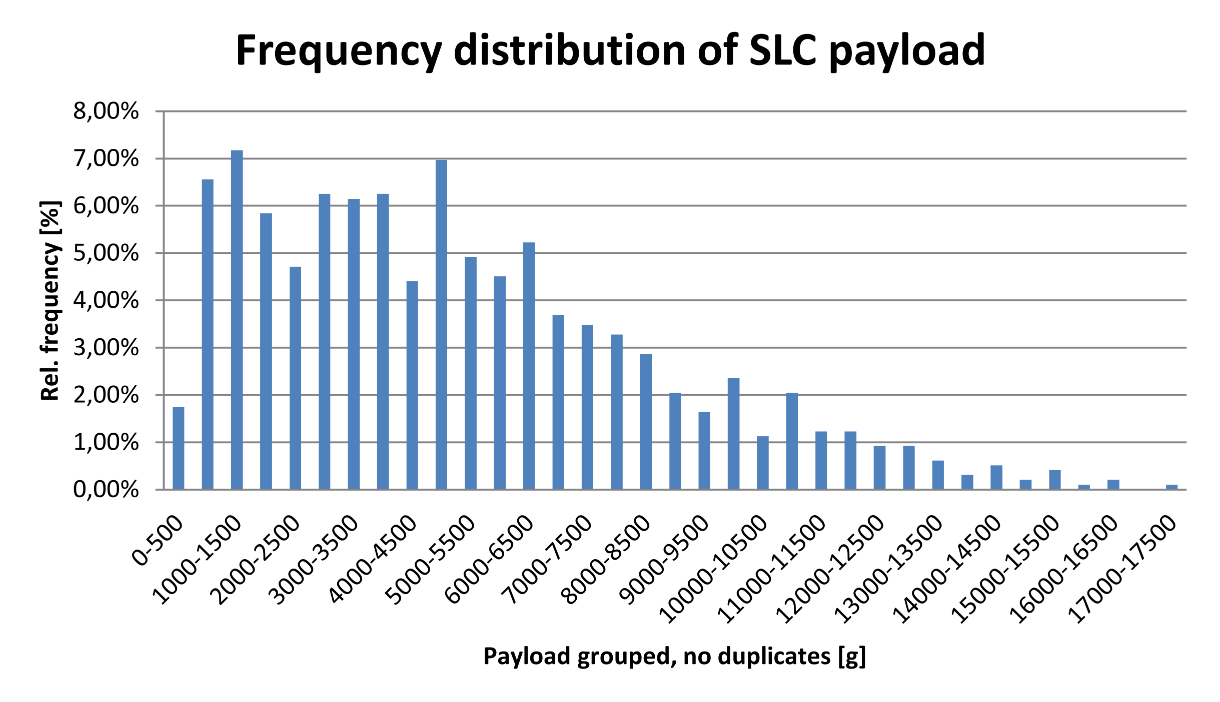


Figure 64: Payload of the SLCs, grouped and sorted but without duplicate mass values

Life data of Shipping Application:

Although the data contained in this log file represents single command cycle and hence, it is not representative for the test methodology that is defined in this thesis, it was also analyzed to see if the results from the previous analysis can be verified in terms of their magnitude. The provided spreadsheet contains the time, the information whether the SLC is stored or retrieved ("INPUT-01" at "src:" resembles storage, "INPUT-01" at "dst:" resembles retrieval), as well as the position of the storage compartment (05/32/9 means carousel nr. 5, x 32/ y 9). An excerpt is shown in Table 51.

Table 51: Excerpt of life data from an SSI SCS horizontal carousel system for a shipping application

22-23:51:11.113	src:	CAROUSEL-SHP05-INPUT-01	dst:	CAROUSEL-SHP-05/CAROUSEL-SHP-05/32/9
22-23:51:21.786	src:	CAROUSEL-SHP05-INPUT-01	dst:	CAROUSEL-SHP-05/CAROUSEL-SHP-05/32/11
22-23:52:23.457	src:	CAROUSEL-SHP-05/CAROUSEL-SHP-05/26/7	dst:	CAROUSEL-SHP05-INPUT-01
22-23:52:49.941	src:	CAROUSEL-SHP05-INPUT-01	dst:	CAROUSEL-SHP-05/CAROUSEL-SHP-05/2/7
…	…	…	…	…

The code that was used to analyze the data is nearly identical to the modules that were already presented. Therefore, the modules are presented in few words.

Module 8 is used to determine the movement along the x-coordinate. It executes the following:

- Transformation of the information regarding storage position from a text to numbers (e.g. CAROUSEL-SHP-05/CAROUSEL-SHP-05/33/2 -> x = 33)
- Calculation of the difference between each carrier position from order to order[88]
- Calculation of the mean, max and min of the difference either dependent on or independent of the turn direction
- Determination of the turn direction (left, right, none, indifferent) and correction of the turn directions of the carousel, if applicable[89]
- Number and frequency of approaches for each carrier

Findings:

The following insights could be made:

Table 52: Findings of module 8 of the shipping application

Minimum carrier number	1
Maximum carrier number	41
Turns to the right	459
Turns to the left	605
No turns	1024
Turn direction not clear (indifferent)	10
Mean travel distance of carousel in x-coordinate[90]	5,327 positions

Figure 65 shows the frequency in which each carrier is approached by the S/R machine. The number that is plotted on the x-axis of the diagram is the actual number of the carrier. It can again be noticed that not all carriers were used within the observation period.

Figure 66 shows the number of positions in x-coordinate that the carousel travels between two different DC cycles. Like Figure 60 the numbers that are plotted on the x-axis are relative numbers that represent the difference between each carrier. The data of the diagram does not take the turn direction into consideration whereas Figure 67 differs between movement to the left (negative sign) and to the right (positive sign). One can again see the bell-shaped distribution of the movement.

[88] The difference resembles the number of positions that the carousel travels between two different orders

[89] The turn direction is revered if the difference is greater than half of the total numbers of carriers (shorter distance)

[90] If the turn direction is not taken into consideration

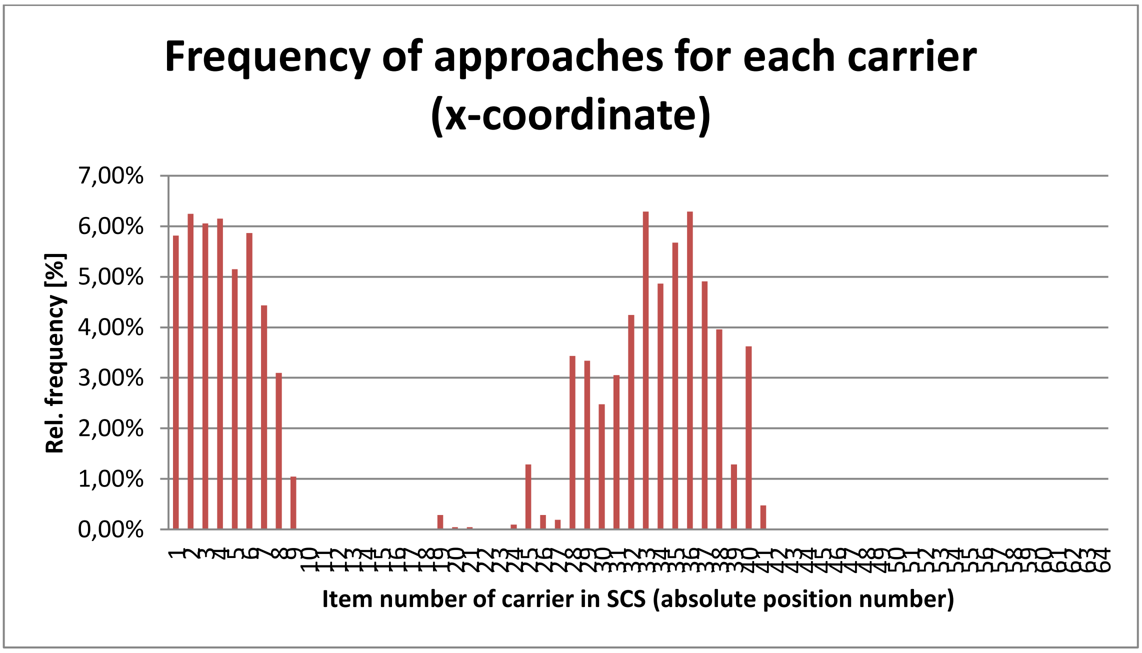


Figure 65: Frequency of approaches for each carrier (x-coordinate)

Module 9 is used to determine the movement along the y-coordinate. It executes the following:

- Calculation of the difference between each level from order to order[91]
- Calculation of the mean, max and min of the difference
- Determination of upward or downward movement
- Number and frequency of approaches for each level

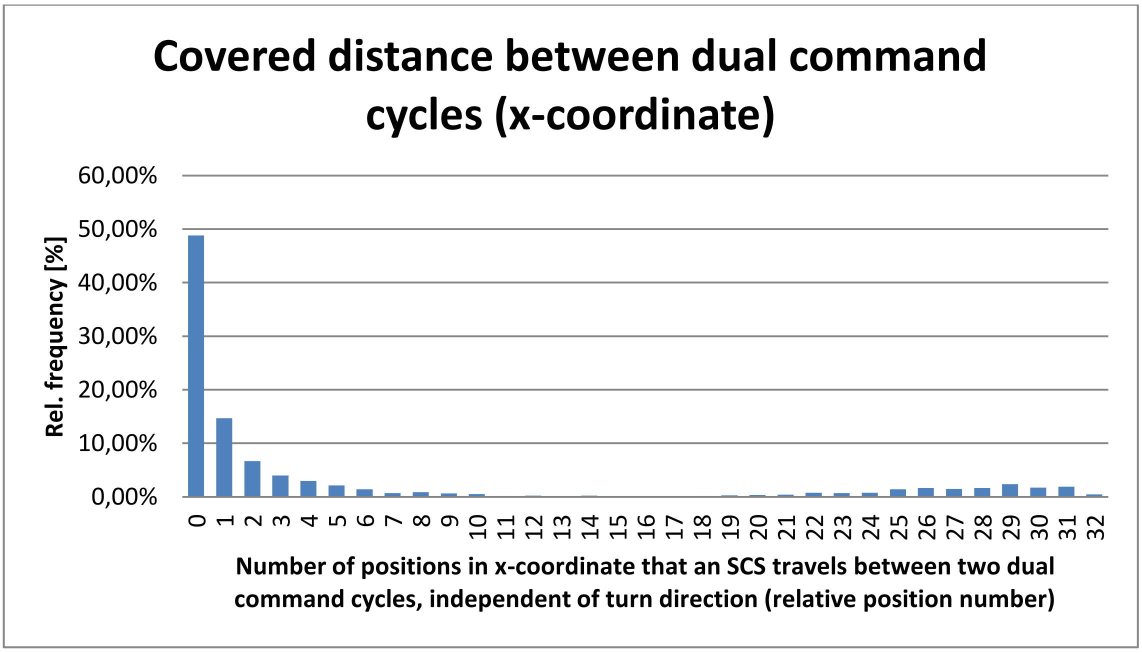


Figure 66: Distance covered by carousel between two double cycles, independent of turn direction

[91] The difference resembles the number of positions that the lift travels between two different orders

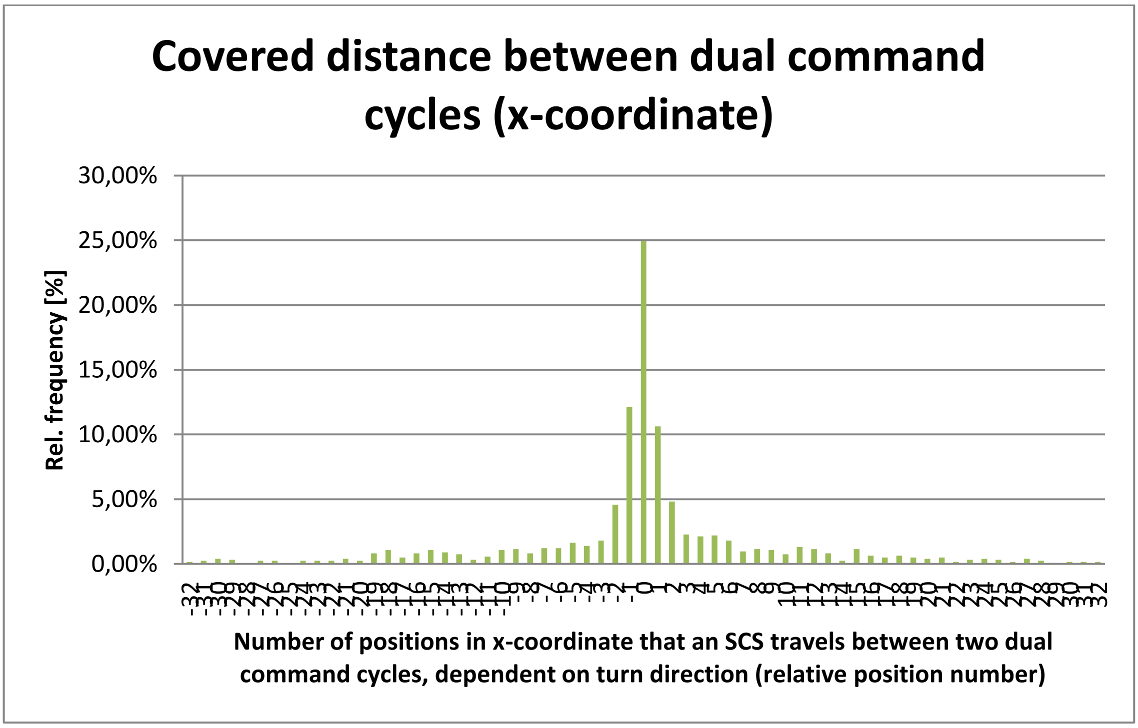


Figure 67: Distance covered by carousel between two double cycles, dependent on turn direction

Findings:

The following insights could be made:

Table 53: Findings of module 9 of the shipping application

Minimum level number	2
Maximum level number	15
Upward movements	980
Downward movements	721
No movement	397
Mean travel distance of lift in y-coordinate	3,549

Figure 68 shows the frequency in which each level is approached by the S/R machine. The number that is plotted on the x-axis of the diagram is the actual number of the storage level. Again, level number one was never approached due to structural conditions. The I/O point is located at the same level as before (nr. three).

Figure 69 shows the number of positions in y-coordinate that the lift travels between two different DC cycles. The numbers that are plotted on the x-axis are again relative numbers that represents only the covered difference.

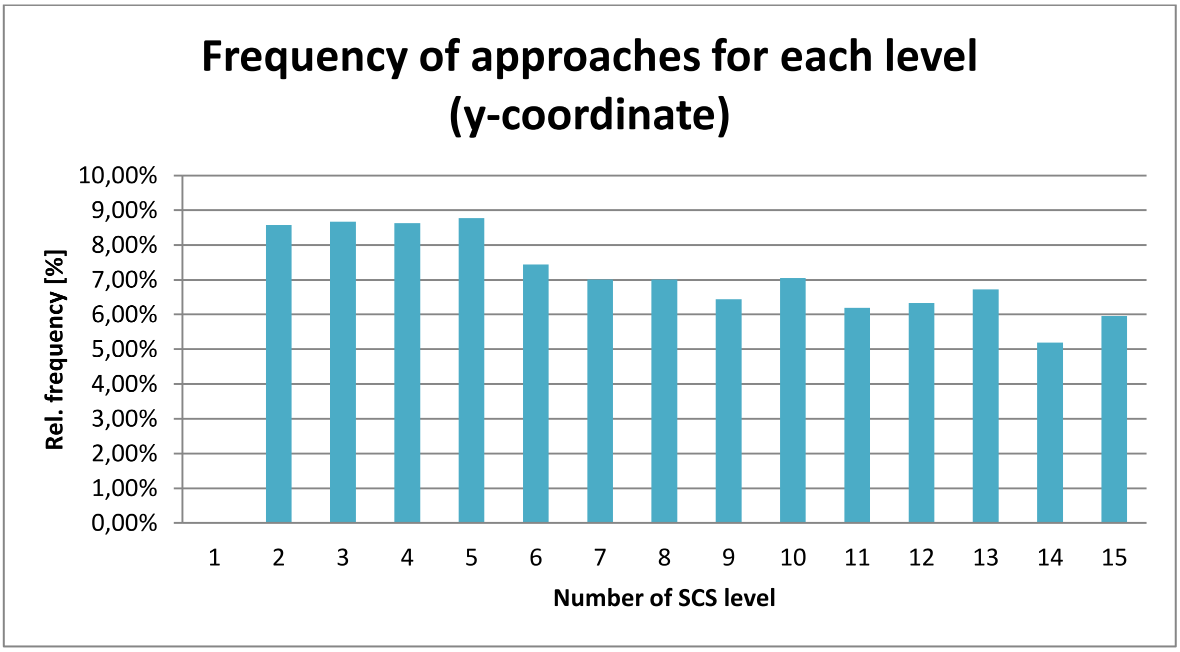


Figure 68: Frequency of approaches for each level (y-coordinate)

The data behind Figure 69 does not take the direction of movement into consideration. Looking at Figure 70 one can see the same data, but with a distinction between upward and downward movement. Again the curve is bell-shaped. In average the lift of a horizontal carousel system travels 3–4 positions between two storage and retrieval orders.

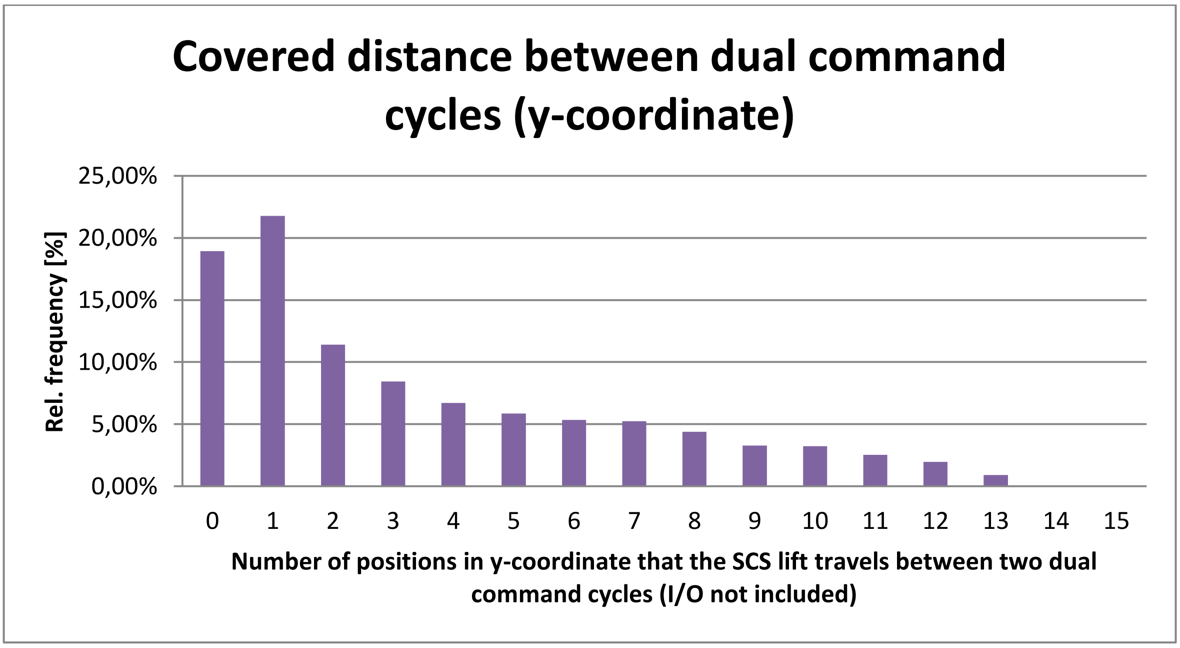


Figure 69: Distance covered by lift between two double cycles, independent of direction of movement

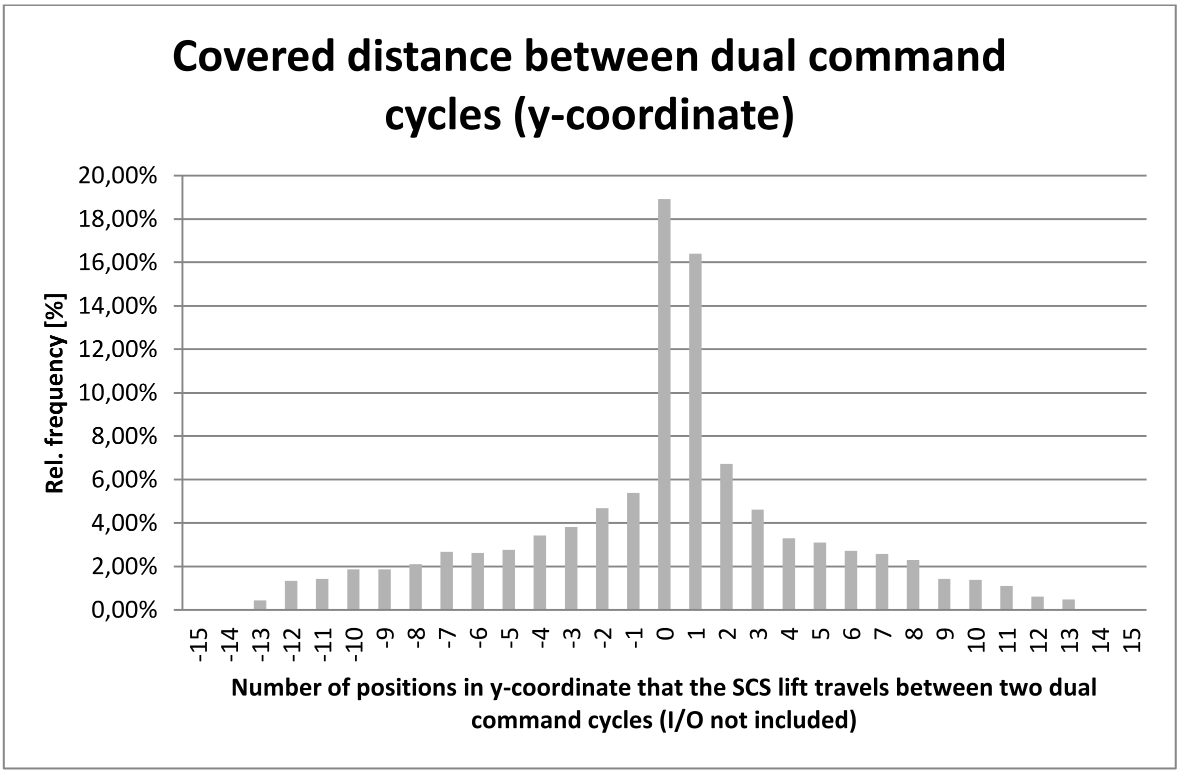


Figure 70: Distance covered by lift between two double cycles, dependent on direction of movement

Module 10 is used to determine the movement along both the x- and the y-coordinate at the same time. It determines if the previous and the next storage position differ and writes the answers “yes” or “no” into the specified column. Like Module 3 it simply checks if there is a difference in the position number of the storage compartments in x- and y-coordinate.

Module 11 is used to determine the total length of the track that the lift travels. It therefore calculates the difference of positions between the current position and the I/O point, as well as the difference between the I/O and the next compartment and simply adds up the numbers. The calculation is based on the same assumption as before.

Findings:

The following insights could be made:

Table 54: Findings of module 11 of the picking application

All movements include approach of I/O point at level 3	
Minimum travel distance of lift in y-coordinate	0 positions
Maximum travel distance of lift in y-coordinate	24 positions
Mean travel distance of lift in y-coordinate	10,214 positions
Minimum track	0 mm
Maximum track	6400 mm
Mean track	2723,609 mm

Recommendations

To draw a conclusion out of the previously mentioned findings, it is recommended to define the representative operating cycle for the horizontal carousel system in such way that the x-coordinate has to move five positions in average to reach the next reference point. According to representatives of the company SSI Schäfer Peem, this number is true for all their horizontal carousel systems no matter how many carriers are mounted on the chain conveyor. The system is always programmed to perform as little x-coordinate movement as possible, since the total mass of the carousel has to be moved.

Further, the movement of the y-coordinate shall be 25% of the total number of levels that the horizontal carousel system consists of. The reason for specifying this movement as a relative number is due to the fact that the number of levels strongly depends on the size of the SLC that the plant operator necessitates. Hence the height of the shelves fluctuates more compared to the number of carriers.

3.5.3.4 ROC in shuttle systems

The definition of a proper representative operating cycle that can be performed by a shuttle system is not straightforward. Especially when considering the boundary conditions that the ROC has to be analog or equal to other ROCs. Hence, there are two possibilities on how to solve the problem. The first approach is to transform the reference points with a shelf unit parameter $w = 1$ defined in VDI 3561 and FEM 9.851 to shuttle systems, in a similar way it was already attempted for horizontal carousel (see chapter 3.3.2)[92]. Obviously, this approach is also quite complex but since shuttle and miniload systems have much more in common than horizontal carousel systems, this might be a feasible method. The second approach is to proceed with a derivation of reference points from scratch, which means using the formulas for the cycle times. As already outlined, these formulas can be found in VDI 2692. The main difficulty for both approaches is to overcome the problematic of the separated movement of the vertical lift and the horizontal vehicle. This leads to two separated movements or in the other case two isolated integrals that have to be considered individually.

For both approaches a general distinction has to be made in advance, because in a shuttle system there are several possibilities how a double cycle can be defined. It strongly depends on the equipment of the system, especially the lifting device. The options could be either:

- Lifts at the front and/or back of the rack system carrying bins or containers (SLC)
    - In general there are two units, one serving the ingoing material flow and the other the outgoing one. Therefore each lift is performing single cycles only, while the shuttle vehicle does perform double cycles.
- Lifts at the front, back or side of the racking system
    - This configuration is used for systems where the shuttle vehicles can change the level. Here the lift can perform a double cycle.

[92] Although the shelf unit parameter does not exist for shuttle systems

Since level-changing shuttle systems tend to be the exception rather than the rule[93], these systems are not taken into account. This thesis is the first attempt to define a standardized measurement procedure, hence, it would be favourable to take a closer look at these complex devices in a second investigation.

Distance-based equivalence of VDI 3591 and FEM 9.851

Dual command cycle is performed by one shuttle in a single level

The SLC is picked up by the lift at the I/O point and hoisted into the desired level. After being dropped into the buffer zone, the corresponding shuttle picks it up again and stores the container in the defined storage compartment. The vehicle then travels further to the next defined compartment, where a second bin is picked up that is now to be retrieved by the system. The bin is then handed over to the buffer zone and the lift respectively, which moves the SLC to the I/O point.

The distances to and from the storage compartements that serve as reference points need to follow certain boundary conditions since the distance between the two reference points shall be equivalent to the diagonal track that a miniload system would perform in a double cycle.

$$l_{diag} = \sqrt{\left(\frac{14}{30} l_{RM}\right)^2 + \left(\frac{14}{30} h_{RM}\right)^2} \qquad \text{Equation 106}$$

Hence the total rack length l_{RM} can be divided into three tracks:

$$l_{RM} = l_{P1} + l_{diag} + l_{P2} \qquad \text{Equation 107}$$

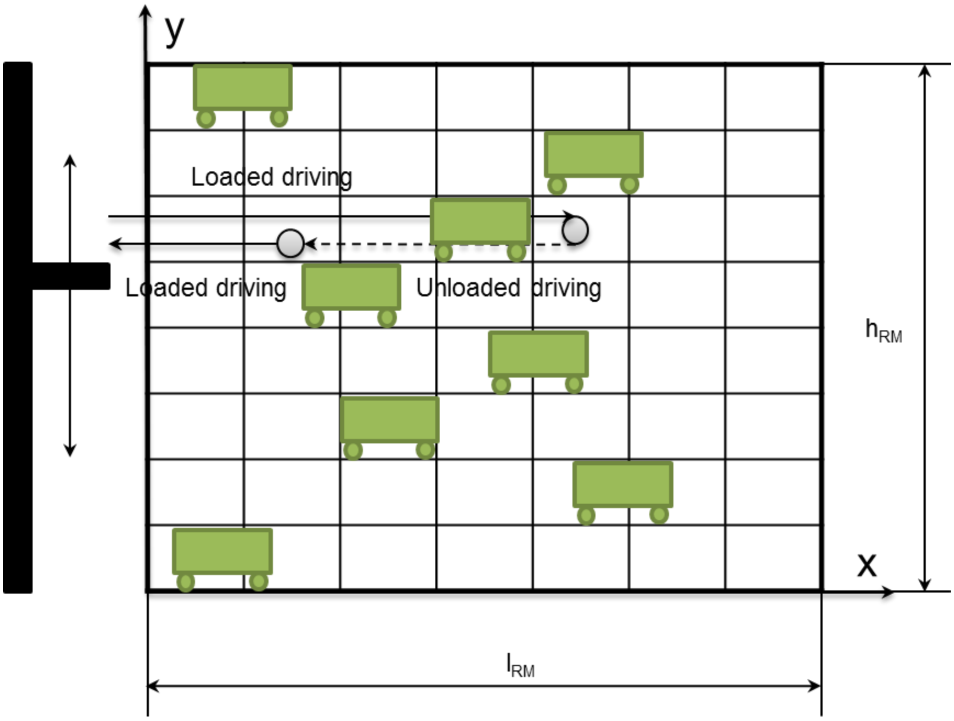


Figure 71: Double cycle by a shuttle vehicle in a single level

93 Compare curve-traversing miniload systems

Table 55: Nomenclature of calculation scheme for reference points in shuttle systems

Nomenclature	
l_{P1}	Length measured from the rack's edge to the first reference point
l_{P2}	Length measured from second reference point to the other edge
l_{diag}	Diagonal track length (miniload system)

Further, the ratio between l_{RM} and h_{RM} has to be equal to the ratio that was defined and used when calculating the dimensions of the virtual rack system. A common ratio that can be found quite often in practice is

$$\frac{l_{RM}}{h_{RM}} = \frac{x}{1} \qquad \text{Equation 108}$$

where x can be any integer $x = 1, 2, 3 \dots u$ depending on the real situation. Often $x = 4$.

In the case the first and last storage compartment are used as reference points, $l_{P1} = l_{P2} = 0$, which means that $l_{RM} = l_{diag}$.

$$l_{RM} = \sqrt{\left(\frac{14}{30} * l_{RM}\right)^2 + \left(\frac{14}{30} * \frac{1}{x} * l_{RM}\right)^2} \qquad \text{Equation 109}$$

$$l_{RM}^2 = \left(\frac{14}{30} * l_{RM}\right)^2 + \left(\frac{14}{30}\right)^2 * l_{RM}^2 * \frac{1}{x^2}$$

$$1 = \left(\frac{14}{30}\right)^2 + \left(\frac{14}{30}\right)^2 * \frac{1}{x^2}$$

$$x^2 - \left(\frac{14}{30}\right)^2 * x^2 = \left(\frac{14}{30}\right)^2$$

$$x^2 * \left(1 - \left(\frac{14}{30}\right)^2\right) = \left(\frac{14}{30}\right)^2$$

$$x_{1,2} = \pm\sqrt{\frac{\left(\frac{14}{30}\right)^2}{\left(1 - \left(\frac{14}{30}\right)^2\right)}}$$

$$x_{1,2} = \pm 0{,}5276$$

This result is not as favorable as expected. In fact it inverts the common ratio, which means that the rack is higher than longer. This is very unusual. Therefore this method has to be withdrawn.

Two single cycles are performed by two shuttles in two different levels

Another possibility is to adopt the reference points and its distances directly. The major drawback in this case is that neither the lifts nor the vehicles perform double cycles. At the upmost one can claim that the system overall is performing a dual command. But it actually does not represent the practice.

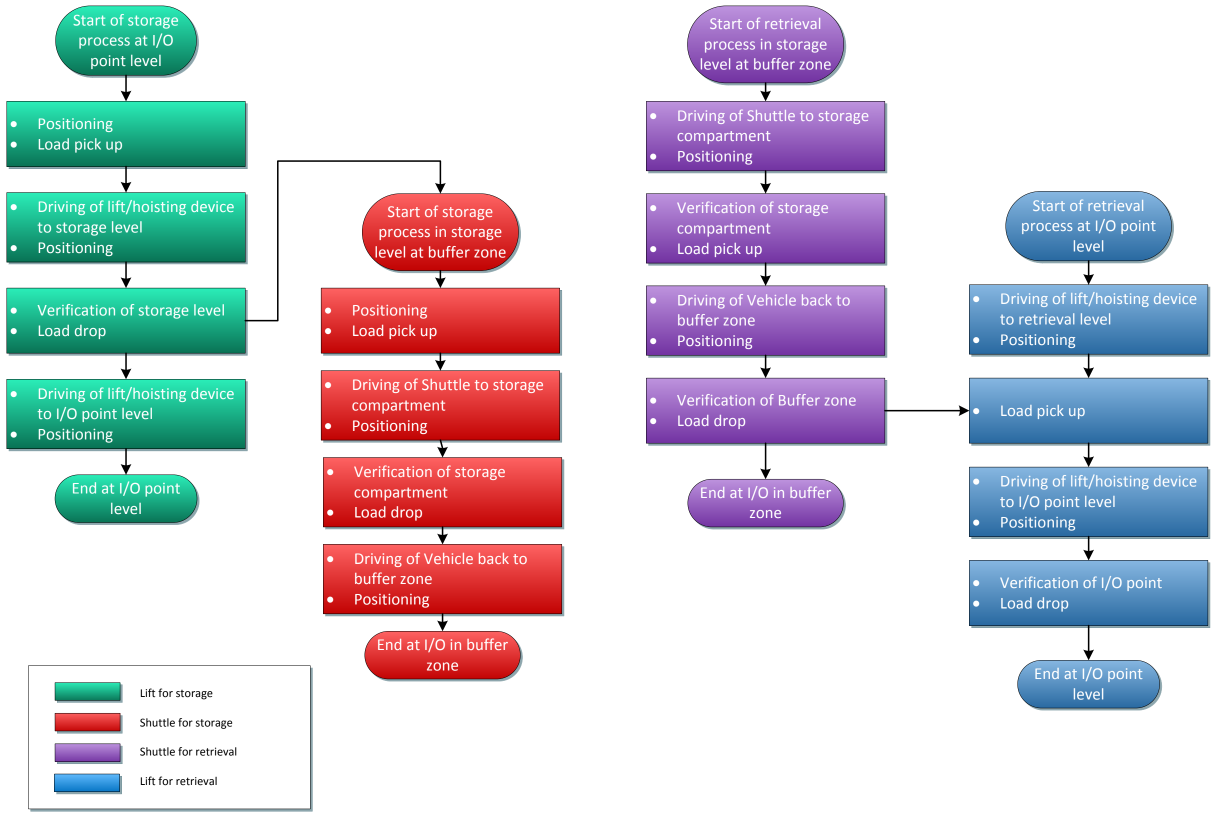


Figure 72: Total operating cycle of the system with direct adoption of miniload reference points

Definition via cycle times according to VDI 2692

To recall chapter 2.5.2.1, the definitions of the mean cycle time for a double cycle performed by a shuttle vehicle shall be mentioned again:

$$\mathrm{t_{SD,x} = t_{FD,x} + 2 * t_{G,x} + 2 * t_{G,x} + \left(3 * \omega_{0,x}\right) * t_{p,x}}$$

With:

$$t_{FD,x} = 2 * t_{FE,x} + \sum_{m=1}^{n_x - 1} \omega_{m,x} * t(m * l_x)$$

And:

$$t_{FE,x} = \frac{1}{n_x} * \sum_{k=1}^{n_x} t((k-1) * l_x)$$

A single cycle performed by each of the two lifts is:

$$t_{SE,y} = 2 * (t_{FE,y} + t_{G,y} + t_{P,y})$$

With:

$$t_{FE,y} = \frac{1}{n_y} * \sum_{k=1}^{n_y} * \, t\left(\left|l_{EAP} + (k-1) * l_y\right|\right)$$

In contrast to miniload systems theses movements are not necessariliy conducted simultaneously. Thus for calculating the travel time of devices with one-dimensional movement the operations of travel time calculations and averaging the distance are interchangeable with sufficient accuracy, if the majority of movements reaches $v = v_{max}$ (trapezoid movement). ([Gud10], p. 624)

By choosing the right velocity pattern the following is applicable according to ([Gud10], p. 624): For a one-dimensional movement, the mean travel time between the points of a line is the same as the time needed for the mean distance between these points. Further the mean distance between two neighboring points out of n ordered points of a line with the total length L is:

$$s_n = \frac{L}{n+1}$$ Equation 110

Two special cases out of Equation 110 are:

- The mean distance between the end and any random point of a line with the length L is $\frac{\mathrm{L}}{2}$ if the frequency of approaches is high enough.
- The mean distance between two random points of a line with the length L is $\frac{\mathrm{L}}{3}$ if the frequency of approaches is high enough.

This basic approach shall now be used to find the right reference points, that resemble the same travel and hence, the same cycle time as the mean cycle time of all storage compartments. Thus the reference operating cycle would be like this:

- The lift travels to the level $\frac{H}{2}$ since only the travel time is considered (the downtime and cycle time of the load handling device are always constant values)
- The shuttle in this level would take over the container and travel to the first position $\frac{\mathrm{L}}{3}$ and store the container into that storage compartment
- The shuttle travels to the second position $\frac{2}{3} * \mathrm{L}$, retrieves another container from this storage compartments and travels back to the buffer zone
- The lift takes the container and travels back to the I/O point

This method should resemble the mean cycle time for the whole rack and can be used as the reference operating cycle of shuttle systems.

3.5.4 Definition of EEIs

The derivation of an energy efficiency indicator model was already discussed in the first chapters 1.4.2 - 1.4.4. The specific energy demand is the starting point of the following considerations.

$$Specific\ energy\ demand = \frac{1}{Energy_{efficiency}}$$ Equation 111

$$E_C = \frac{1}{E_{eff}} = \frac{E_E}{W_L}$$ Equation 112

3.5.4.1 Energy demand E_E

The power consumption P_i that is measured during each phase of the representative operating cycle is multiplied by the corresponding portion of time T_i. All phases summed up result in the total energy demand of the ROC and equals the amount that is necessary to store and retrieve small load carriers.

$$E_E = \sum_{i=1}^{n} P_i * T_i \qquad \text{Equation 113}$$

With the constraint:

$$T_i = T_n * t_i \qquad \text{Equation 114}$$

The energy demand equals:

$$E_E = T_n * \sum_{i=1}^{n} P_i * t_i \qquad \text{Equation 115}$$

3.5.4.2 Logistic performance W_L – model 1

Since the main function of automated storage and retrieval systems is the input and output of small load carriers into a warehouse, the total number of storage and retrieval processes in a certain time period is of particular interest. Hence the easiest way to describe the benefit that is generated using the system is simply taking this number as a reference value. Further the throughput is also known, because the time period of the operating state is already defined.

$$W_{L(SLC)} = X_{ges} \qquad \text{Equation 116}$$

The total number of SLCs is the sum of SLCs counted in each operating state. It can also be expressed via the throughput and time interval.

$$X_{ges} = \sum_{i=1}^{n} X_i = \sum_{i=1}^{n} \Lambda_i * T_i \qquad \text{Equation 117}$$

$$T_i = T_n * t_i \qquad \text{Equation 118}$$

The logistic performance $W_{L(SLC)}$ based on the number of SLCs equals:

$$W_{L(SLC)} = T_n * \sum_{i=1}^{n} \Lambda_i * t_i \qquad \text{Equation 119}$$

With the already presented formula to calculate the energy demand:

$$E_E = T_n * \sum_{i=1}^{n} P_i * t_i \qquad \text{Equation 120}$$

The specific energy demand is calculated according to:

$$E_{eff} = \frac{W_L}{E_E} \qquad \text{Equation 121}$$

$$E_C = \frac{\cancel{T_n} * \sum_{i=1}^{n} P_i * t_i}{\cancel{T_n} * \sum_{i=1}^{n} \Lambda_i * t_i} \qquad \text{Equation 122}$$

Unit: $[\frac{Wh}{SLC}]$

Advantages:

This model indicates the most important criteria of AS/RS namely the throughput. The unit can be described as tangible and consequentially comprehensive as it is expressed by energy demand in Wh per single bin that is either stored or retrieved. By means of personal discussions it become obvious that this approach will be widely supported by the sector of logistics engineering.

The major advantage of this model can be seen in conjunction with the defined load spectrum. By using the sum of all operating states in the formula, the Standby period can also be referred to the throughput. Hence in total the energy consumption rises whereas the logistic performance stays the same. This maps the reality in an appropriate way, as the model assigns a better energy efficiency indicator to all AS/RS with a lower energy consumption in standby mode.[94] This is not possible with any other approach since then the calculation would result in a division by zero. That is also the only reason why ([SFB13b], p. 201) does not recommend the throughput as reference value. The same problem of referring to no logistic benefit also arises in ([EG13], p. 10) because there the methodology of the guideline VDI 4707 is transferred to stacker cranes.

Disadvantages:

At a first glance, one might not recognize that this method is based on the throughput, because it is hidden within the definition of the ROC. The mean cycle time and hence the throughput rate Λ_i is already pre-defined by the position of the reference point whereas the time period T_i for each operating state is defined additionally and summed up to $T_N = 1\ h$.

The unit of the indicator is de facto Wh only. It is more conceivable to refer to the number of small load carriers.

3.5.4.3 Logistic performance W_L – model 2

Model number two is a modification of model number one. It is achieved by merging the number of total inputs and outputs to the number of double cycles that are performed during a representative operation cycle.

$$W_{L(DC)} = N_{ges} \qquad \text{Equation 123}$$

The total number of dual command cycles is the sum of double cycles counted in each operating state.

$$N_{ges} = \sum_{i=1}^{n} n_{DS} \qquad \text{Equation 124}$$

The double cycles can be calculated by dividing the time period by the cycle time needed by the AS/RS.

[94] This statement is also true for the other models that are defined in this thesis

$$n_{DS} = \frac{T_i}{T_{cycle,\,i}}$$ Equation 125

But it can also be expressed via the consideration that a double cycle always consists of a storage and a retrieval process.

$$X_i = 2 * n_{DS}$$ Equation 126

$$\sum_{i=1}^{n} n_{DS} = \sum_{i=1}^{n} \frac{X_i}{2} = \frac{1}{2} * \sum_{i=1}^{n} \Lambda_i * T_i$$ Equation 127

$$T_i = T_n * t_i$$ Equation 128

The logistic performance $W_{L(DC)}$ based on the number of double cycles equals:

$$W_{L(DC)} = T_n * \frac{1}{2} * \sum_{i=1}^{n} \Lambda_i * t_i$$ Equation 129

When inserting the argument:

$$E_E = T_n * \sum_{i=1}^{n} P_i * t_i$$ Equation 130

The specific energy demand is calculated according to:

$$E_C = \frac{E_E}{W_L}$$ Equation 131

$$E_C = \frac{\cancel{T_n} * \sum_{i=1}^{n} P_i * t_i}{\cancel{T_n} * \frac{1}{2} * \sum_{i=1}^{n} \Lambda_i * t_i}$$ Equation 132

Unit: $[\frac{Wh}{SLC}]$

Advantages/Disadvantages:

De facto model 1 and model 2 are identical except for the scaling factor of $^1/_2$.

The unit of the indicator is Wh per double cycle (in SI-units Wh only), but again this is more conceivable when including the number of dual command cycles.

3.5.4.4 Logistic performance W_L – model 3

Another approach seems to be quite attractive when designing indicators that appeal especially to horizontal carousel systems. Since the total mass is constantly moved, one might consider the payload of the small load carrier as a benefit. The logistic performance is calculated by summing the total mass that is transported into or out of the rack system during a ROC.

$$W_{L(payload)} = M_{ges}$$ Equation 133

The total payload is the product of SLCs times the payload in each operating state.

$$M_{ges} = \sum_{i=1}^{n} M_i * X_i$$ Equation 134

$$M_i = M_n * m_i$$ Equation 135

$$M_{ges} = M_n * \sum_{i=1}^{n} m_i * X_i$$ Equation 136

$$W_{L(payload)} = M_n * \sum_{i=1}^{n} m_i * X_i$$ Equation 137

It can also be expressed via the throughput and time interval.

$$\sum_{i=1}^{n} X_i = \sum_{i=1}^{n} \Lambda_i * T_i$$ Equation 138

$$W_{L(payload)} = M_n * \sum_{i=1}^{n} m_i * \Lambda_i * T_i$$ Equation 139

$$T_i = T_n * t_i$$ Equation 140

$$W_{L(payload)} = T_n * M_n * \sum_{i=1}^{n} \Lambda_i * t_i * m_i$$ Equation 141

With the already presented formula to calculate the energy demand:

$$E_E = T_n * \sum_{i=1}^{n} P_i * t_i$$ Equation 142

the specific energy demand is calculated according to:

$$E_C = \frac{E_E}{W_L}$$ Equation 143

$$E_C = \frac{\cancel{T_n} * \sum_{i=1}^{n} P_i * t_i}{\cancel{T_n} * M_n * \sum_{i=1}^{n} \Lambda_i * t_i * m_i}$$ Equation 144

Unit: $[\frac{Wh}{SLC}]$

Advantages:

This model is advantageous if one is interested in the mass that is transported into or out of an automated storage and retrieval system during a representative operating cycle. The unit of the indicator expresses the energy demand in Wh per kg that is either stored or retrieved. Hence it only consists of SI base units. Further, the advantages regarding the defined load spectrum that were already stated in model 1 do apply here as well.

Disadvantages:

Unfortunately, the payload of the SLCs are not documented in general. The SLCs and the items have to be weighted in an additional process step. Furthermore the unit is not as tangible as the others, since the mass varies from SLC to SLC.

4 Methods for evaluation of AS/RS

This chapter describes the necessary steps in order to perform a standardized measurement. One of the most critical things when evaluating automated storage and retrieval systems is to ensure reproducibility. Due to that, sticking to the outlined guideline and a consistent documentation is vital. Like all evaluation methods in this research project, this guideline consists of three phases: planning, measuring and analysis of data, as it is shown in Figure 73.

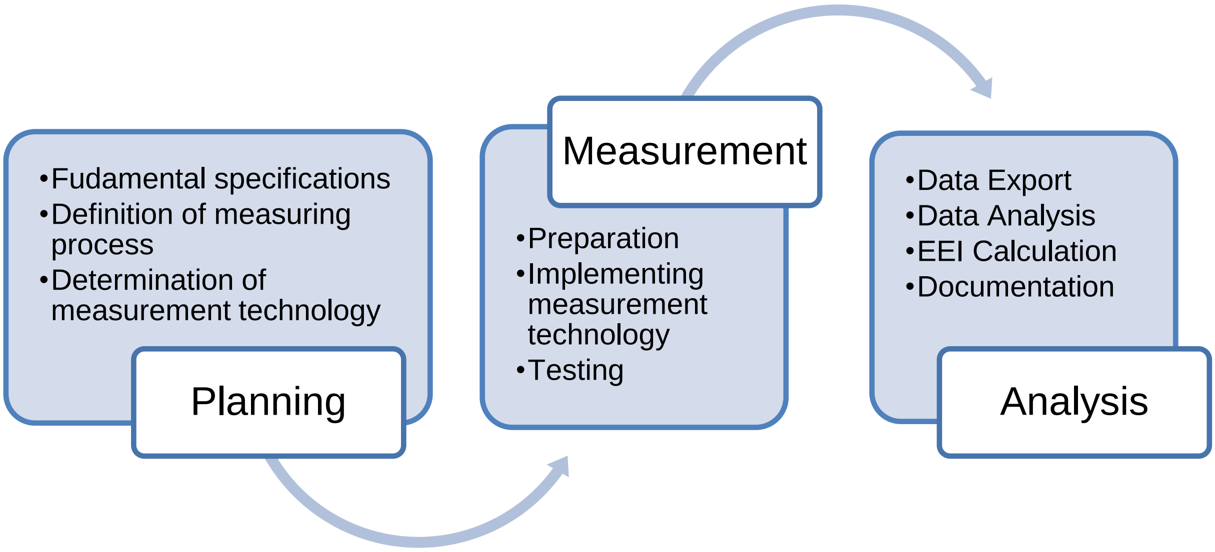


Figure 73: Overview of process steps when evaluating an AS/RS

The first process step is the planning phase, which includes all preparations, that are required to conduct a series of measurements. Determination of fundamental specification is followed by defining the exact sequence of each step in the measurement process. Several parameters, which are of particular interest determine the measurement technology. This technology of course is to be used in the next step, the measurement phase. It starts with preparing the object, which is to be tested, as well as implementing and configuring the measurement technology. The conduction of real test series is the last process step during the measurement phase. During this phase it is vital to take all necessary boundary constraints, rules and regulations into consideration. Finally the retrieved data has to be analyzed accordingly. This is done by exporting, preparing and treating the data so that the energy efficiency indicators can be calculated and documented accordingly. The methodology and the calculation scheme for the energy efficiency indicators of this chapter shall be valid for all systems regardless of the technology. Some specific characteristics of each system gain their influence later in the process.

4.1 Planning and design of the testing procedure

A thorough planning of the testing procedure is necessary for all downstream activities. Therefore one has to get acquainted with the automated storage and retrieval systems, which are to be compared. Ideally, the planning of the energy efficiency evaluation is done parallel to the planning and design of the warehouse in such a way, that the testing can take place before the system is used in practice. The testing can also be combined with the technical certification and approval process, which is required for new machines. Otherwise, one has to assure that the evaluation does not disturb any productivity process going on. This is of course quite complex or sometimes even not possible. It is further to be welcomed, that the manufacturer themselves start to implement energy efficiency evaluations and start to publish the results like it is done for lifts (VDI 4707), refrigerators or car tires.

In general, the planning starts by documenting and assessing the systems as a whole. In order to do this, one has to understand all aspects of the system, which includes both the logistical aspects (type of application, material flow scheduling, storage assignment strategies, etc.) as well as the technical data and specifications. For example, it is important to study the circuit diagrams in order to understand where to actually plug the measurement equipment or to understand the way the AS/RS systems can be programmed in order to perform the necessary representative operating cycles.

4.1.1 System boundaries of automated storage and retrieval systems

In order to live up to the mentioned vendor independence, it makes sense to consider the fully automatic storage system as a black box, since a black box is a system without any knowledge of its internal processes.

Figure 74: Considering the system as a black box[95]

This means, that the system boundaries include the complete construction ranging from drive trains, regulator control elements to control systems and thus covers everything that is necessary to store a unit load. Furthermore, it enables the direct confrontation of input and output of the system, as can be seen in Figure 74. As a direct consequence of the black box approach, it also makes sense to exclude manually controlled or semi-automated systems and to concentrate on fully automatic storage systems only. The reasons are, that this method ensures that no random human influence is taken into account.

[95] (Cf. [SFB13b], p. 200)

4.1.1.1 System boundaries of a miniload system

Figure 75 shows a miniload system and the system boundaries, which are used for determining and measuring the power demand. The point of measurement includes all electric appliances of the AS/RS system.

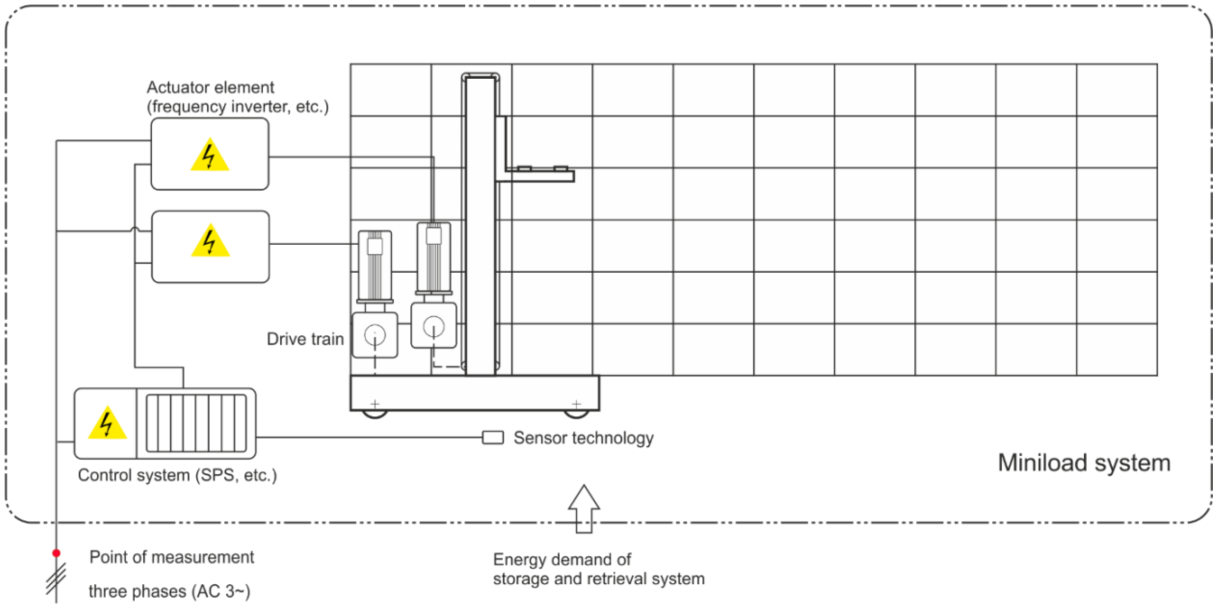


Figure 75: System boundaries of a miniload system

4.1.1.2 System boundaries of a horizontal carousel system

Figure 76 shows a horizontal carousel system and the system boundaries, which are used for determining and measuring the power demand. The point of measurement includes all electric appliances of the AS/RS system.

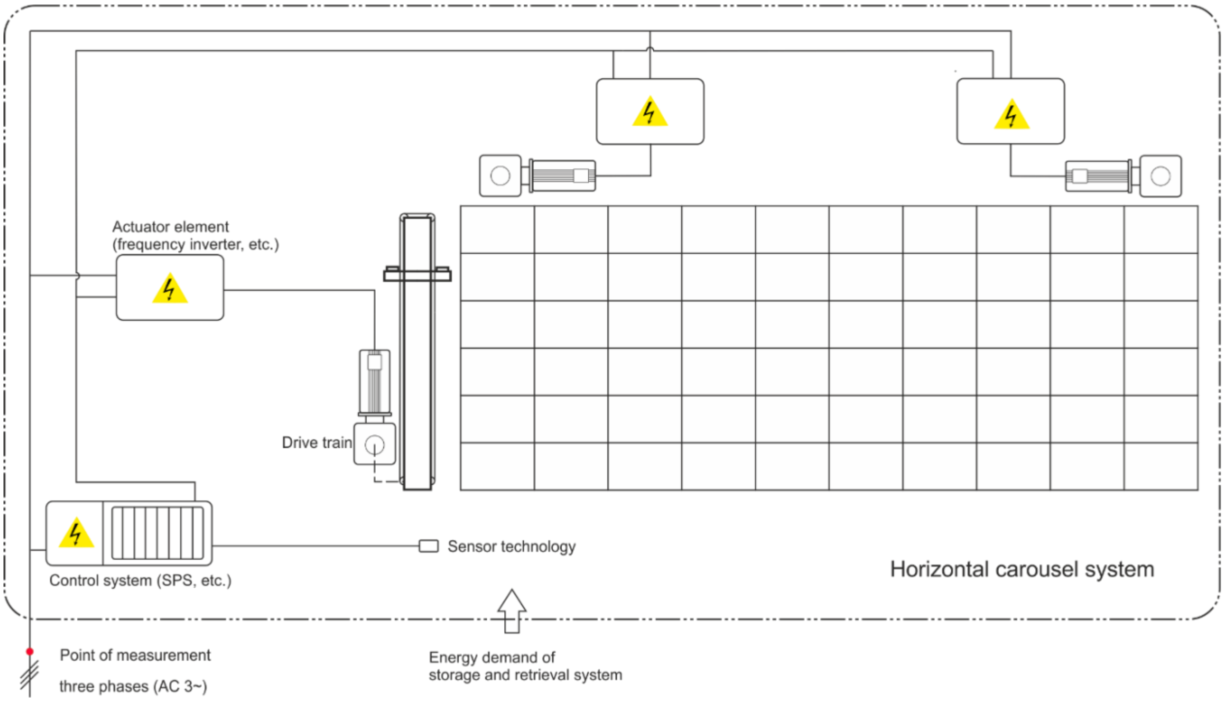


Figure 76: System boundaries of a horizontal carousel system

4.1.1.3 System boundaries of a shuttle system

Figure 78 shows a shuttle system and the system boundaries, which are used for determining and measuring the power demand. This diagram is only valid if the shuttle vehicle is rail-bound, which means, that the energy supply of the shuttle vehicles is achieved via conductor rails, like it can be seen in Figure 77.

Figure 77: Conductor rails of a KNAPP OSR shuttle system[96]

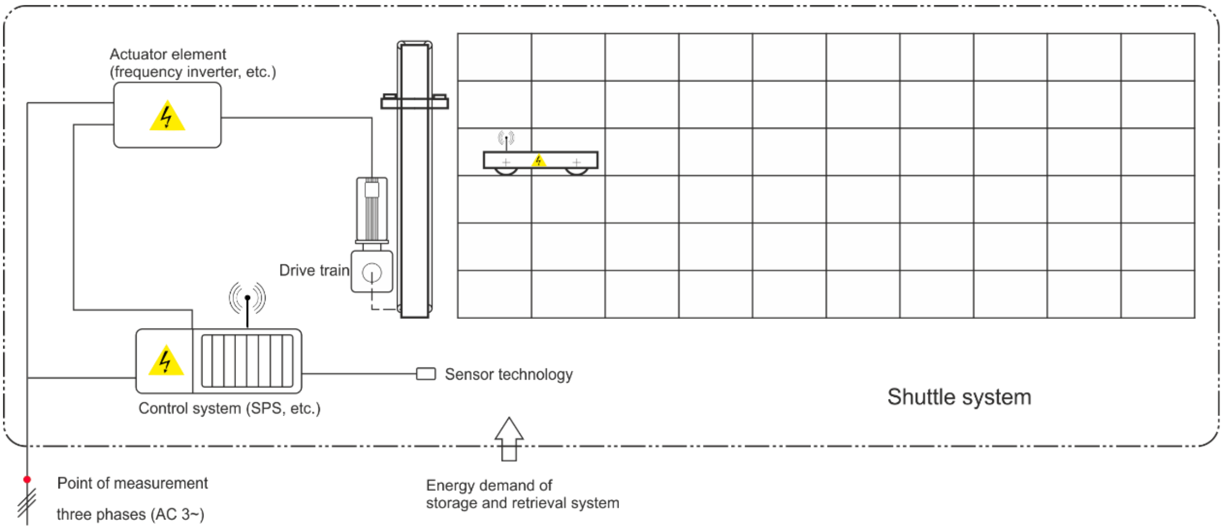


Figure 78: System boundaries of a shuttle system

[96] http://knapp.com/cms/download.php?downloadId=429&languageId=1

All other drive concepts, which are used for shuttle vehicles, like accumulators or super-/ultracaps have be considered individually. This is because the black box approach would lead to false values, since it would include the charging of these mobile energy sources while the representative operating cycle does not necessarily consume the total energy, which was stored during the charging process.

Therefore one has to differentiate between three system variants:

- Conductor rails: proceed with black box approach, because all energy appliances are included.
- Super-/Ultracap: Since the endurance of such energy sources is generally limited to a few minutes, the black box approach can be used if and only if the endurance is somehow comparable and of the same magnitude to a double cycle or at least the time it takes to measure an operating cycle. The situation, where the demand for a double cycle is exactly the same as the energy, which is stored in the super-/ultracap would be ideal. In this case the vehicle has to be recharged after each task.
- If the super-/ultracap is capable of handling a vast amount of double cycles or if the vehicle is equipped with an accumulator, which supplies power for several hours, then the vehicle has to be measured on its own. There are at least two possibilities to achieve this. Option one is to fully charge the accumulator and run the vehicle until the accumulator is drained. The amount of energy needed for a double cycle can then be calculated by dividing the capacity by the total numbers of performed double cycles. This procedure has to be done for each operating state of the representative operating cycle. Option two is far more complicated, since it requires the measurement equipment to be stored on the vehicle. Thereby, the accumulator is fully charged again and a double cycle performed. During the run, the energy demand can be measured. This has to be repeated for each operating state as well. Whether option is chosen, the demand has to be added to the demand of the rest of the system, which is measured using the black box approach.

4.1.2 Definition of the measuring methodology

In this phase it is essential to recall the basics of measuring the electrical power. It is measured as electrical energy per time interval by means of physical principals like induction or digital by integrating the electrical energy over time. All information of this chapter can be found in ([Müh08], p. 165 ff.).

4.1.2.1 Active, reactive and apparent power

Direct current

In the easiest case, the power output of a DC circuit can be measured. If the voltage U is applied and a current I flows through an electric consumer, the power P can be calculated as the product by simple multiplication:

$$P = U * I \qquad \text{Equation 145}$$

Alternating current

By using the Fourier-analysis every non-sinus curve can be transformed to a sinus wave. Hence, the momentary values of voltage and current are defined as:

$$u(t) = \hat{U} * \sin(\omega * t + \varphi_u)$$ Equation 146

$$i(t) = \hat{I} * \sin(\omega * t + \varphi_i)$$ Equation 147

Table 56: Nomenclature of electro-technical measurands

Nomenclature	
$\hat{U}, \hat{I}$	Amplitudes of voltage and current
φ_u, φ_i	Phase angles of voltage and current
U, I	Effective or RMS-values of voltage and current
P	Mean power

$\hat{U}$ and $\hat{I}$ are the amplitudes, while φ_u and φ_i are defined as the phase angles. Because AC is oscillating periodically around null, it is necessary to form the effective or RMS-value (root mean square). The effective values are equivalent to the ones found in DC systems and enable the comparability. The RMS values of voltage and current are:

$$U = \frac{\hat{U}}{\sqrt{2}}$$ Equation 148

$$I = \frac{\hat{I}}{\sqrt{2}}$$ Equation 149

The power can also be calculated by multiplying the momentary values of the voltage and current:

$$p(t) = u(t) * i(t) = \hat{U} * \hat{I} * \sin(\omega * t + \varphi_u) * sin(\omega * t + \varphi_i)$$ Equation 150

When inserting the addition theorem:

$$\sin(\alpha) * \sin(\beta) = \frac{1}{2} * (\cos(\alpha - \beta) - \cos(\alpha + \beta))$$ Equation 151

the power is:

$$p(t) = U * I * \cos(\varphi_u - \varphi_i) - U * I * \cos(\omega * t + \varphi_u + \varphi_i)$$ Equation 152

The mean power is determined by using the integral:

$$P = \overline{p(t)} = \frac{1}{T} * \int_0^T p(t)dt$$ Equation 153

Together with the previous equation the power is calculated according to:

$$P = \frac{1}{T} * \int_0^T U * I * \cos(\varphi_u - \varphi_i)\, dt - \frac{1}{T} * \int_0^T U * I * \cos(\omega * t + \varphi_u + \varphi_i)dt$$ Equation 154

$$P = U * I * \cos(\varphi_u - \varphi_i)$$ Equation 155

If the phase angles are identical,

$$\varphi = \varphi_{ui} = \varphi_u = \varphi_i$$ Equation 156

then the mean power can be calculated easily. This power P is also called active power.

$$P = U * I * \cos(\varphi)$$ Equation 157

The effective energy is found by further integration:

$$E = W = \int_0^T P(t)dt$$ Equation 158

The active energy can be seen as the area underneath the power curve, which is depicted in Figure 79.

Due to capacitive or inductive loading, energy can oscillate between the generator and the consumer. This oscillating power is also called reactive power Q.

$$Q = U * I * \sin(\varphi)$$ Equation 159

The apparent power S, which equals the amplitudes of the alternating component of $p(t)$ is calculated in the same way, as it is done in Equation 145.

The ratio of reactive to apparent power is called the power factor $\cos(\varphi)$:

$$\cos(\varphi) = \frac{P}{S}$$ Equation 160

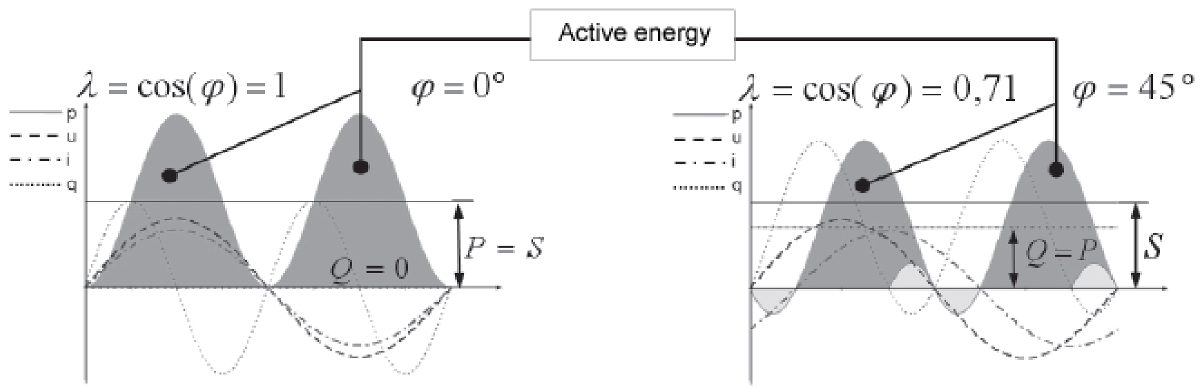


Figure 79: Active and reactive energy with a phase angle of 0° and 45°[97]

4.1.3 Determination of the measurement technology

The technical equipment, which is to be used for measurement has to fulfill high expectations. This paragraph pays special attention to the measurement of alternating current, since the measurement of the power demand has to be done in a three phase AC system.[98] The main challenge of measuring in AC systems is to include non-ideal harmonics. Those harmonics are mainly produced by voltage or frequency converters that are used more often nowadays but can also derive from disturbances of the electric grid like voltage unbalance, flicker or poor power factor. The quality requirements for electric energy in industrial environment are regulated according to DIN EN 50160 and DIN EN 61000-2.

[97] ([Pae13], p. 39)

[98] The only exceptions are shuttle vehicles that use accumulators or supercaps

Thus the measuring device and its sensors have to be very accurate and have to fulfill the following tasks, which are in conformity with VDI 4707[99]:

- Creation of the three-phase effective power (RMS)
- Creation of single-phase effective power
- Consideration of harmonics
- Sufficient measuring range to include both small standby outputs and high acceleration demands
- Ability to determine power output/demand from effective values of the voltage and current by the measuring device
- The effective values must be calculated simultaneously between two unbroken readings/samplings
- Recording of output values during ROC (e.g. graph with power output as a function of time)

Table 57: Measurands and demands on measurement technology

Description	Demands on measurement technology
Voltage (3-phase AC system)	$0 - 400\ \mathrm{V}$
Current (3-phase AC system)	$0 - 10\ A$
Bandwidth	$0 - 300\ kHz$
Sampling Rate	$> 20\ \mathrm{kHz}$

For the measurement process, digital measurement devices are the most promising. At the Institute of Logistics Engineering, the benchtop laboratory instrument Dewetron DEWE-800 is available. This laboratory instrument can be used universally and is very flexible, as it is prepared for up to 16 DAQP isolated input amplifier modules, which can be changed by the user any time. According to its manufacturer Dewetron GmbH, the main advantage of the DEWE-800 is the high galvanic isolation, which ensures a safe measurement and high quality results.[100]

Table 58: Specification of Dewetron DEWE-800

Description	Specification	
High voltage amplifier	Dewetron DAQP-HV	$\pm 50\ V$ $\leq 300\ kHz$ bandwidth
Low voltage amplifier	Dewetron DAQP-LV	$\pm 1400\ V$ $\leq 300\ kHz$ bandwidth
Current probe	Dewetron PROSys CP300	$300\ A\ (DC\ or\ AC_{pk})$

[99] ([VDI09], p. 10)
[100] ([Dew14])

Shunt Dewetron DAQ-SHUNT-4	$\pm 5\,A$

The benchtop laboratory instrument is based on conventional x86 architecture. Therefore, the analysis of the measured data can be done on- and offline using the powerful software DEWESoft. It also features a Fast-Fourier-Transformation Analysis (FFT) of the measured voltages and currents for each individual phase. The algorithm detects the harmonics of each measuring signal including the corresponding amplitude and phase angle. Consequentially the effective values of voltage and current for each phase is calculated.[101]

$$U_{nh} = \frac{\hat{U}_{nh}}{\sqrt{2}}$$ Equation 161

$$I_{nh} = \frac{\hat{I}_{nh}}{\sqrt{2}}$$ Equation 162

$$U_n = \sqrt{\sum_{h=1}^{H} U_{nh}^2}$$ Equation 163

$$I_n = \sqrt{\sum_{h=1}^{H} I_{nh}^2}$$ Equation 164

The RMS value of the active power for a specific harmonic and phase is calculated according to Equation 157. By summing up all harmonics the mean active power of a single phase is derived. The total active power can then be calculated as the sum of all phases.

$$P_{nh} = U_{nh} * I_{nh} * \cos(\varphi_{nh})$$ Equation 165

$$P_n = \sum_{h=1}^{H} P_{nh}$$ Equation 166

$$P = \sum_{n=1}^{3} P_n$$ Equation 167

Table 59: Nomenclature of measurands of a specific phase

Nomenclature	
$\hat{U}_{nh}, \hat{I}_{nh}$	Amplitudes of voltage and current resulting from FFT analysis
φ_{nh}	Phase angles resulting from FFT analysis
U_n, I_n	Effective or RMS-values of voltage and current for phase n
n	Phase number
h	Order of harmonic
H	Number of harmonics
P_{nh}	Active power of considered harmonic in phase n

[101] (Cf. [HL13])

P_n	Active power of phase n
φ_n	Phase angle of phase n
P_{ges}	Total active power

4.2 Measurement

4.2.1 Preparation and implementation of measurement technology

The measurement itself has to be prepared carefully. This phase contains the following activities:

- The small load carrier must be prepared regarding the payloads that fit to the operating states of the ROC. During the effMFS project it turned out, that the simplest way to provide the exact weight is to use wet sand, which is filled into the SLC. Caution must be taken, that the sand cannot escape and damage any machines.
- The points of measurement in the control cabinet have to prepared. It is useful to prepare extra wiring in such a way, that the sensors of the measurement device can be easily connected or removed.
- The measurement device has to be configured and initialized. This is especially true, if a computer is used for the digital measurement. One has to take care, that each measuring channel is setup up according to the wiring diagram and that the signal is free from any disturbances.
- Possibly the AS/RS has to be prepared in some way to perform the representative operating cycles. This has to be done on an individual basis.

4.2.2 Measurement

Beside the already mentioned boundary conditions, the measurement has to be performed under these constraints:

Table 60: General parameters for measurement

General parameters	Regulated values
Temperature	$20° \pm 4°C$
Humidity	$\leq 80\%$
Loading of SLC	$\pm 0{,}25\%$

This helps to ensure that the outcome is reproducible, because the environmental conditions are the same. It is of advantage to perform some test rides before the real measurement samples are take, in order to check the whole setup and each parameter for plausibility.

If everything is correct, the real measurement is to be performed. During the measurement-phase, notes have to be taken, which document the complete process including all possible incidents. The data, which is recorded by the measurement device has to be stored in a safe way and of course has to be named accordingly, so that the files can be assigned to the documentation.

It is suggested to repeat each measurement five times in order to normalize the data. This compensates the random failure impact and enables a statistical treatment of the results.

4.3 Analysis

4.3.1 Data export and analysis

If supported by the measurement equipment, the electrical data shall be processed during the recording process. In general, it would be of advantage that at least each parameter, which has to be integrated over time is treated this way. Any other calculation such as averaging for instance shall also be calculated by the software. Nevertheless any variable and parameter has to be recorded on its own. If the analysis is to be done in any other numerical computer environment, the setup of the export process of the raw data has to documented as well. This activity is useful for any reporting and charting task.

4.3.2 Energy efficiency indicator calculation

The energy efficiency indicators have to be calculated according to the equations of the chapters 3.5.4.2 - 3.5.4.4.

4.3.3 Documentation/Reporting

A template document that shall support the documentation process can be found in the Addendum. The most common features are already pre-filled, whereas any other notation can be written in the empty places. The report shall include:

- Type of AS/RS that has been tested
- Documentation of any special measurement preparation
- Measurement conditions
- Results of the measurement
- Analysis of the measurement (e.g. graphical presentation)
- Calculation of the energy efficiency indicators
- Comparison of reports done for other AS/RS type (if necessary)
- Classification (if possible)

5 Conclusion and perspective

This study presents a new way in comparing and evaluating the energy efficiency of fully automated storage and retrieval systems. Due to the very different nature of miniload systems, horizontal carousel systems and shuttle systems, a new approach was elaborated to provide a complete comparability. During the work, it turned out, that comparability has to be assured on different levels at the same time. In a first step, the equivalency of the three systems has to be established. This is achieved by using the storage capacity as base parameter. In case that the real rack systems are not equal, the virtual rack dimensions can be calculated on this basis. Further, a representative operating cycle was defined, which includes three different operating states ranging from full and partial load to standby. Within each operating state, a small load carrier with a pre-defined payload is stored and retrieved in double cycles for a period of time. Another step in providing comparability was to find specific reference points. These storage compartments have to be chosen in such a way, that the operating cycles for all the systems are equivalent to each other. Then the energy demand can be measured and compared. The reference points were defined individually for each system based upon guidelines VDI 3561, FEM 9.851 and VDI 2692 and real life-data that was provided by the company SSI Schäfer-PEEM Graz. Further, energy efficiency indicator models were defined that contrast the energy demand of a system to its logistical performance. This work features three different proposals for the logistical performance of AS/RS. Depending on which parameter is of more interest, one or all calculation schemes can be applied. Finally, a short but vital step-by-step guide for measuring the power demand is provided in order to determine the energy demand of the system. It features the basics to measure the critical electrical parameters in a proper way and prescribes some constraints and conditions like temperature or humidity as well as the measurement equipment that is to be favored. The testing has to be repeated to exclude random influences. The documentation and analysis of the data is the last step but has to be done as accurate as each step before.

Nevertheless, the evaluation of the energy efficiency of fully automated storage and retrieval systems remains a complex field. Future work has to be done to validate, expand and further improve the proposed measurement method. Of particular interest is the implementation of a criteria list, that enables the classification of energy efficiency, like it was already proposed by ([EG14]). The identification, the definition of threshold values and the classification of the data, which was acquired using the proposed measurement method are subject to further investigation and assessment once the first experienced data is available. Further, the integration of simulation tools would be of a real advantage.

Fortunately, the effMFS project at the Institute of Logistics Engineering is going to be continued. Another project application has been successfully submitted and approved. The focus of the next project will be on the complex architecture of the whole warehouse eco-systems and hence, promotes the holistic approach to determine energy efficiency.

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Addenda

Addendum A: UML models

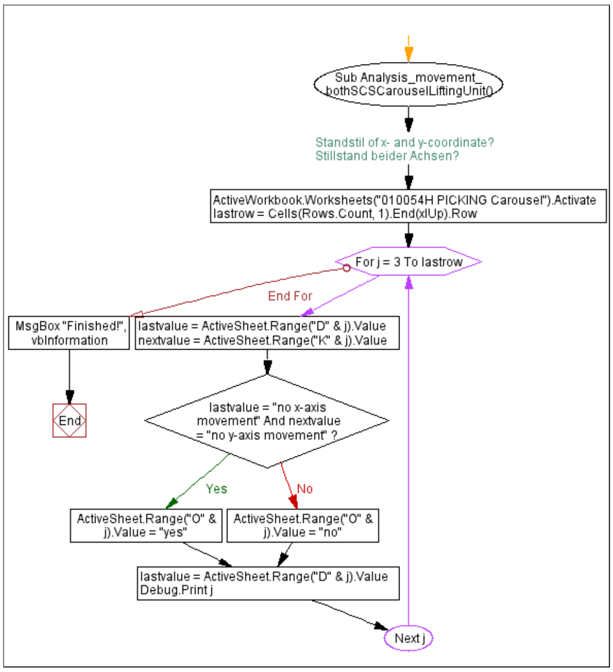


Figure 80: UML model of VBA module 3 that analyses the movement in x and y-coordinate

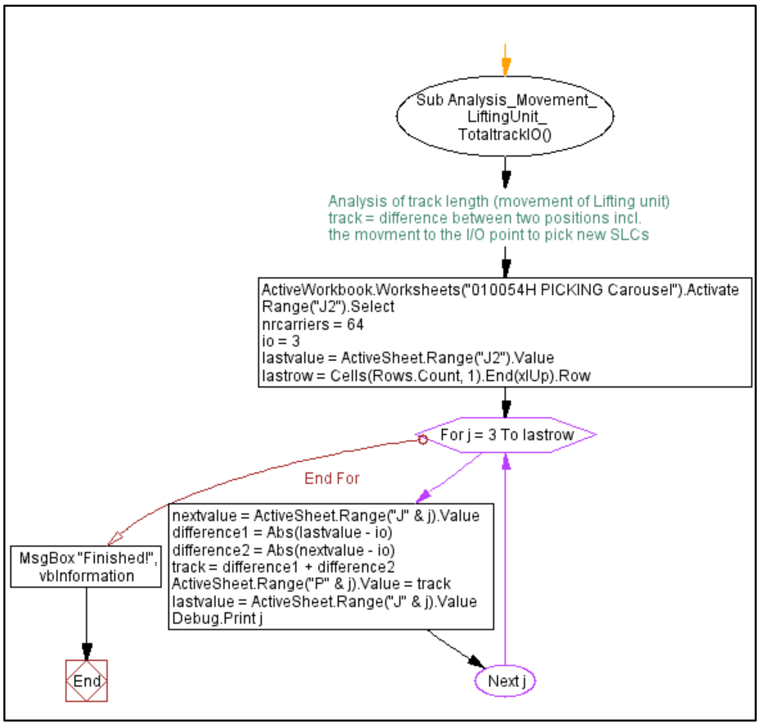


Figure 81: UML model of VBA module 4 that analyses the total track of the carousel

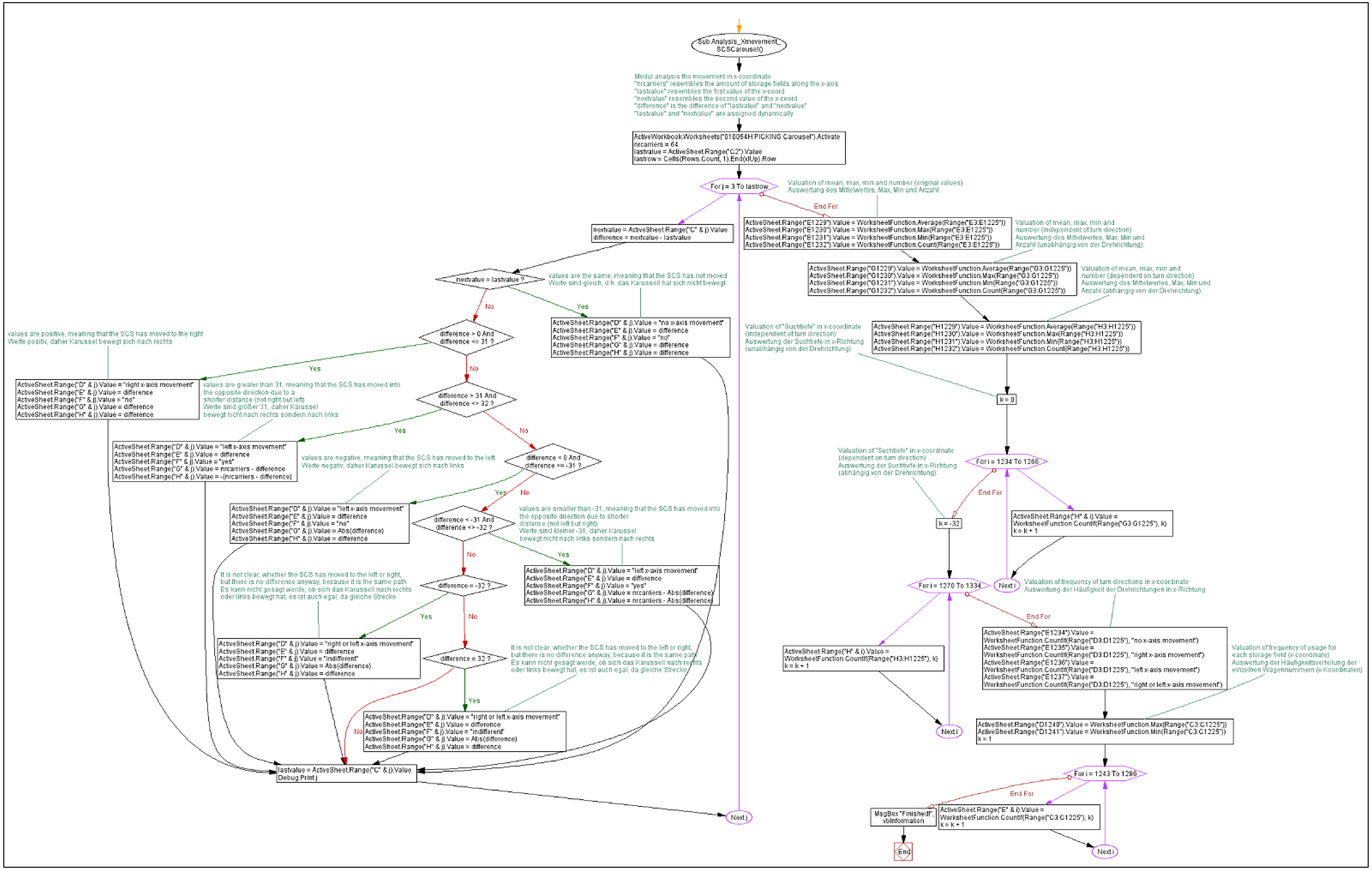


Figure 82: UML model of VBA module 1 that analyses the movement in x-coordinate

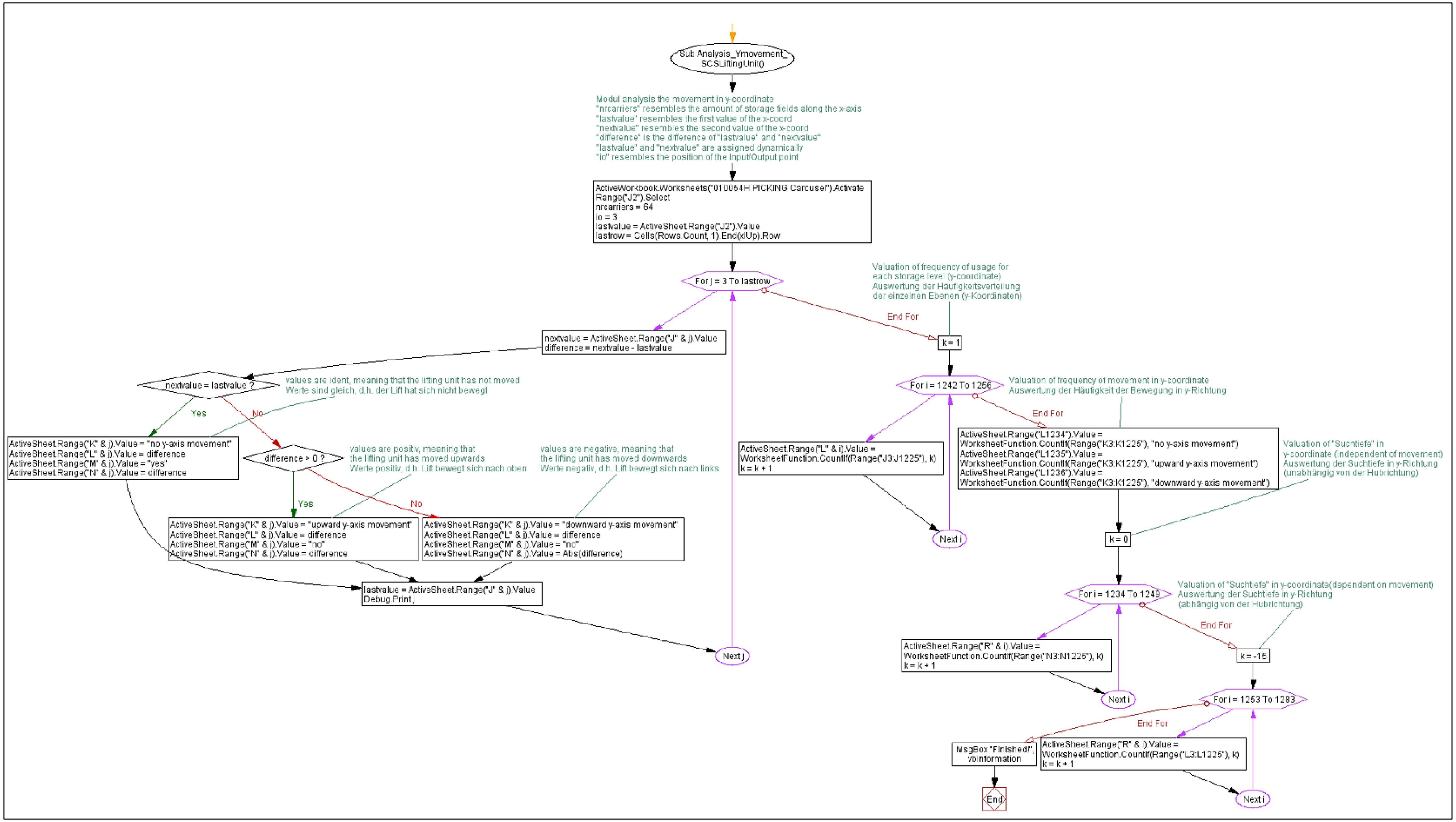


Figure 83: UML model of VBA module 2 that analyses the movement in y-coordinate

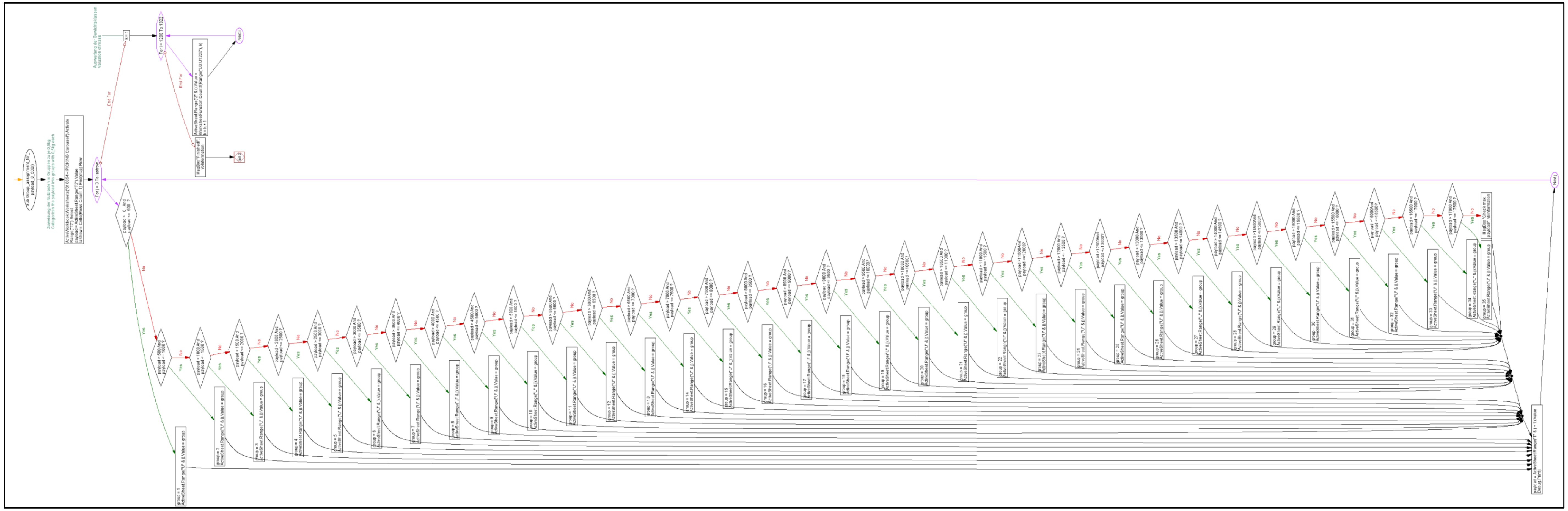


Figure 84: UML model of VBA module 7 that analyses the payload of the horizontal carousel system

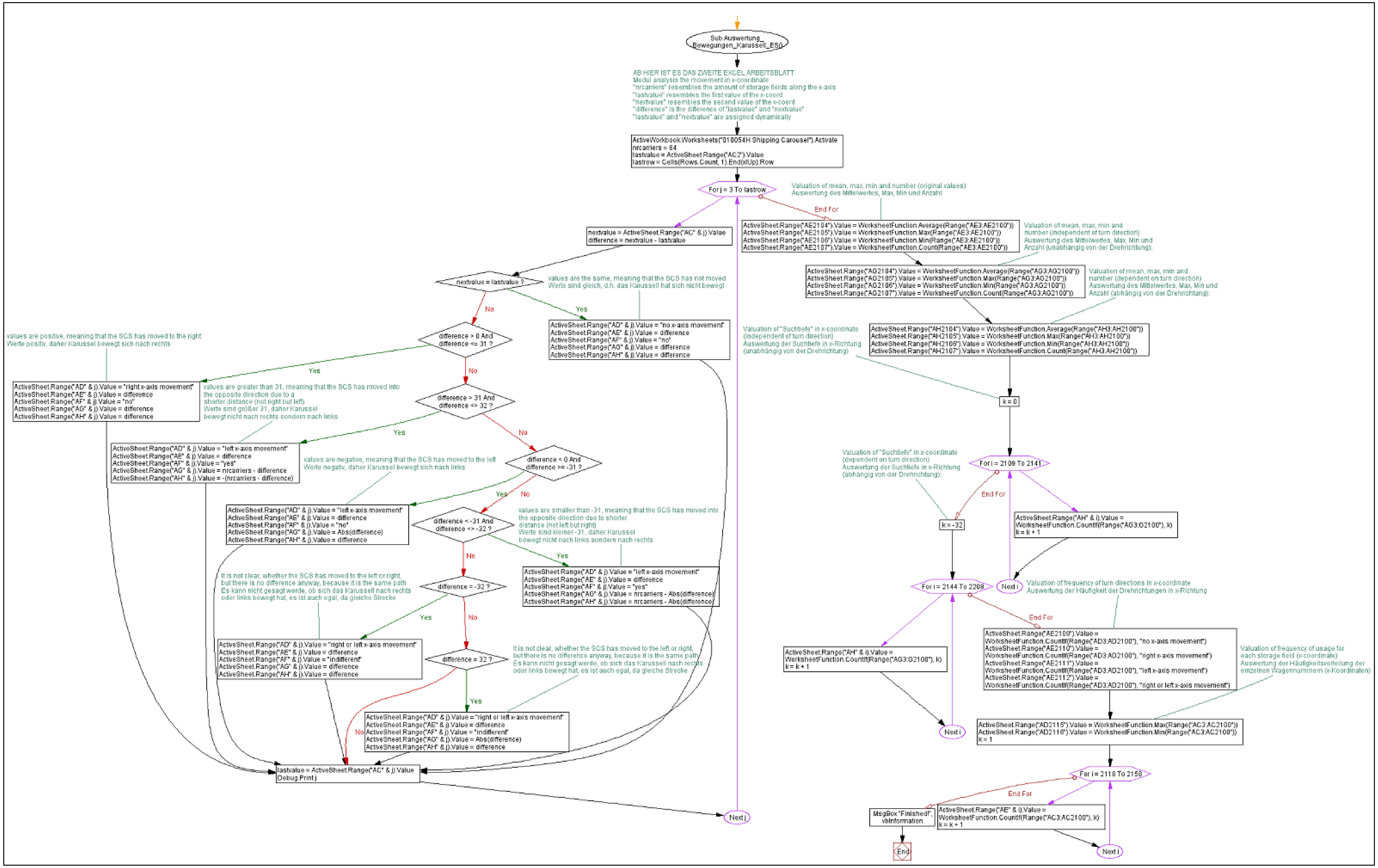


Figure 85: UML model of VBA module 8 that analyses the movement in x-coordinate

Addendum B: Measurement methods for evaluating the specific energy demand

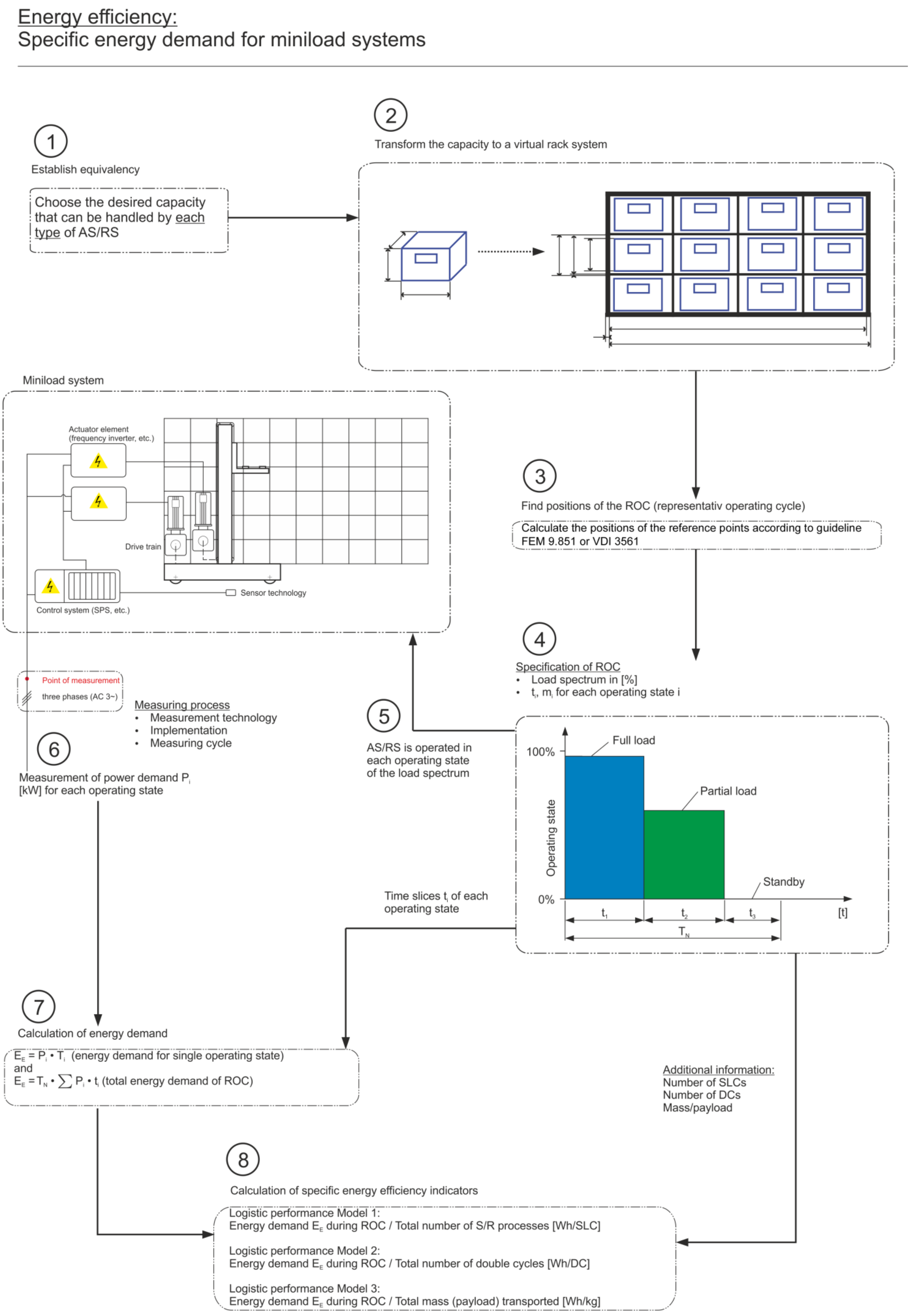


Figure 86: Measurement method for valuating specific energy demand of miniload systems

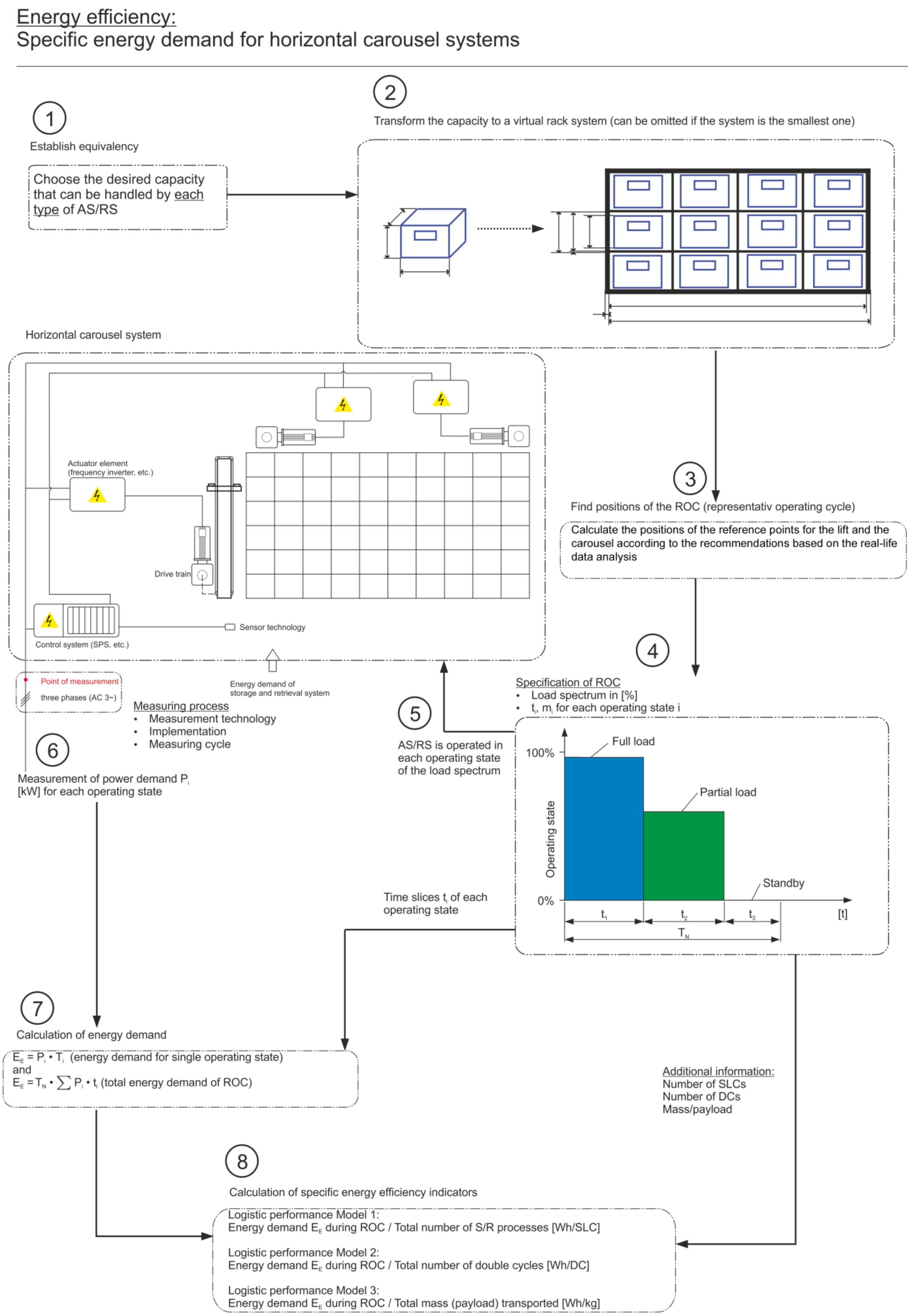


Figure 87: Measurement method for valuating specific energy demand of horizontal carousel systems

Energy efficiency:
Specific energy demand for shuttle systems

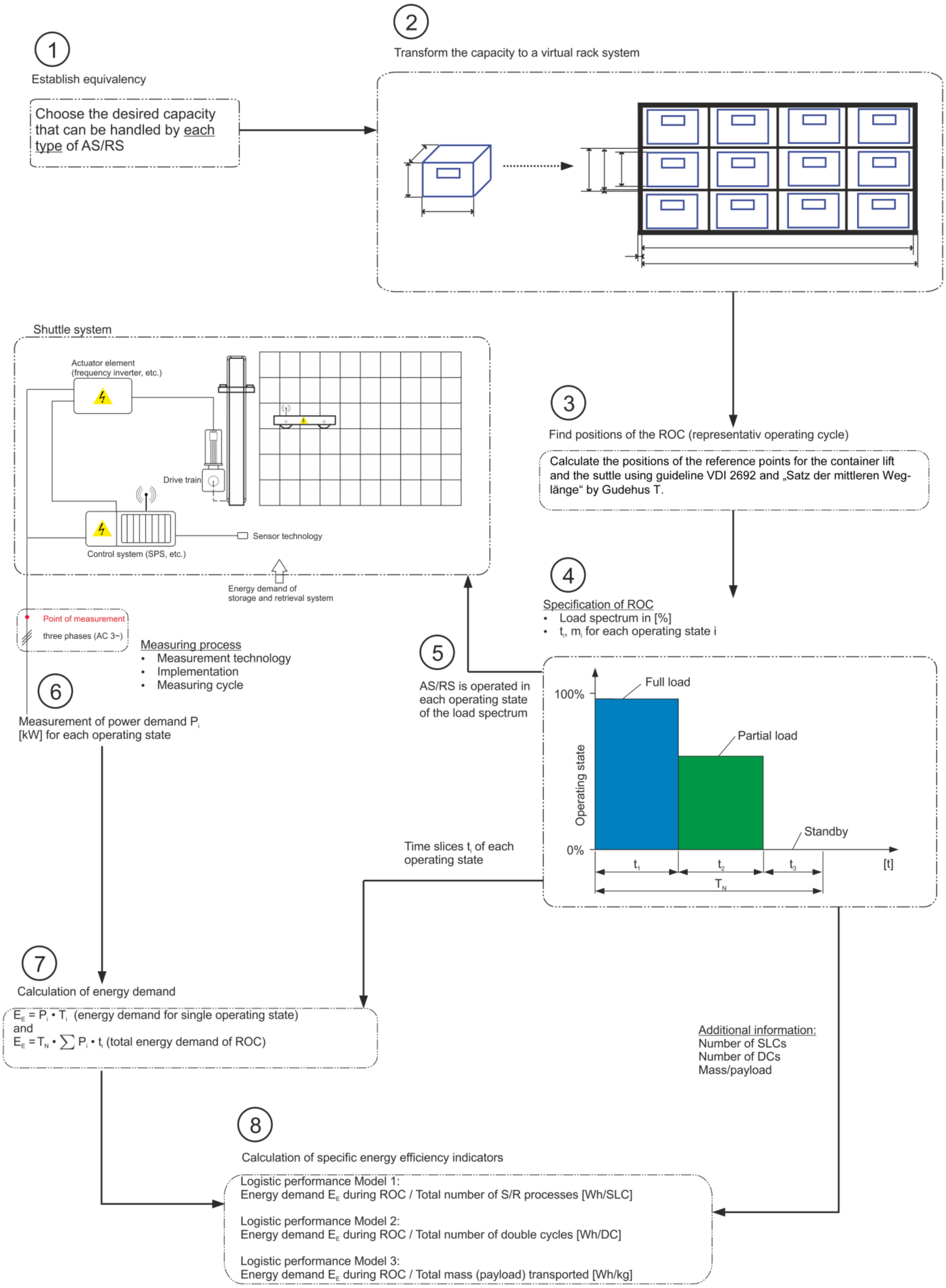


Figure 88: Measurement method for valuating specific energy demand of shuttle systems

Addendum C: Screenshot of virtual rack system calculation tool

Dimensionen Lagerfach			
Breite des Lagerfaches	*b_LF*	*445*	mm
Tiefe des Lagerfaches	*t_LF*	*655*	mm
Höhe des Lagerfaches	*h_LF*	*390*	mm
ACHTUNG: Hier die Abmaße der Kisten des SCS eingeben			
Breite der Ladeeinheit	b_LE	400	mm
Höhe der Ladeeinheit	h_LE	300,0	mm
Tiefe der Ladeeinheit	t_LE	600	mm
ACHTUNG: Die Höhe der Ladeeinheit h_LE muss kontrolliert werden			
Höhe der Ladeeinheit (berechnet)		296,3	
ACHTUNG: Hier die Abmaße des RBG eingeben			
Tiefenfreimaß	z_Frei	55	mm
Höhenfreimaß	y_Frei	90	mm
Seitenfreimaß	x_Frei	22,5	mm
Abstand in x-Richtung zwischen Ladeeinheiten	x_LE-LE		mm
Abstand in x-Richtung zwischen Ladeeinheiten und Steher	x_LE-S		mm
Traversenhöhe	h_T	2,5	mm
Steherbreite	b_ST	60	mm
Aushubhöhe Ladungsträger bei einfachtiefer Lagerung	y_et		mm
Freimaß in z-Richtung (Regalgasse)	z_Frei_G	100	mm
Abstand in z-Richtung zwischen den Ladeeinheiten bei doppeltiefer Lagerung	z_RF-RF		mm
Lagerfachkapazität (Einheiten pro Lagerfach)	c_LP	1	#
Dimensionen Fachmodul			
Breite des Fachmoduls	*b_FM*	*505*	mm
Tiefe des Fachmoduls	*t_FM*	*655*	mm
Höhe des Fachmoduls	*h_FM*	*392,5*	mm
ACHTUNG: Hier die Abmaße des RBG eingeben			
Anzahl Lagerfächer in der Horizontalen	n_H	32,5	#
Anzahl Lagerfächer in der Vertikalen	n_V	14,59395	#
RBG Breite	t_BG	650	mm
Arbeitsgangbreite	A_st	850	mm
Unteres Anfahrmaß	UAM	285	mm
Umschlagmenge	n_ea	250	1/h
Doppelspielanteil	DA	100	%
Einzelspielanteil	EA	0	%
Anzahl der Einzelspiele/h	ES	0	1/h
Anzahl der Doppelspiele/h	*DS*	247,5248	1/h
Höhe des SCS		4700	
Anzahl der Wägen des SCS		64	
Anzahl der Stellplätze pro Wagen des SCS		15	
Stellplätze (Soll aus Karussell)		*960*	#
Anzahl der Gassen des RBG		1	#

Ladeeinheiten pro RBG Gasse		*960*	#
Anzahl der Regalwände pro RBG Gasse		2	#
Ladeeinheiten pro RBG Regalwand		*480*	#
Fächer pro RBG Regalwand		*480*	#
Anzahl der Regalfächer je Regalzeile		*474,3033*	#
Verhältnis Regallänge/Regalhöhe		*2,87*	

Anzahl Spalten (Lagerfächer in der Vertikalen)	*n_V2*	*14,59*	
Anzahl Spalten (Lagerfächer in der Vertikalen)	*n_Vgew*	*15,00*	
Anzahl Spalten (Lagerfächer in der Horizontalen)	*n_H2*	*32,50*	
Anzahl Spalten (Lagerfächer in der Horizontalen)	*n_Hgew*	*32,00*	
Kontrolle der Gesamtstellplätze		***960***	#

Dimensionen Regalmodul

Länge des Regalmoduls	*l_RM*	*16220*	mm
Breite des Regalmoduls	*b_RM*	*2160*	mm
Höhe des Regalmoduls	*h_RM*	*6172,5*	mm

Ungefähre Teilung der Regalwand in der Länge		*506,875*	mm/La
Ungefähre Teilung der Regalwand in der Höhe		*411,5*	mm/La

Reale Teilung der Regalwand in der Länge		*500*	mm/La
Reale Teilung der Regalwand in der Höhe		*371*	mm/La

Referenzpunkte AKL mit Ausgangspunkt SCS		FEM	
Referenzpunkte 1	P1		
Abstand	*P1x*	3244	mm
	P1y	4115	mm
Koordinaten	*P1x*	6	
	P1y	11	
Referenzpunkte 2	P2		
	P2x	10813,33	mm
	P2y	1234,5	mm
Koordinaten	*P2x*	22	
	P2y	3	

Figure 89: Screenshot of MS Excel file that helps calculating virtual rack dimensions

Addendum D: Measurement report

Measurement report „AKL“

Table of content

1 Planning

1.1 General information:

General information:			
Editor:		Date:	
Time:		Location:	
File location:			

1.2 Fundamental specification and technical data

1.2.1 System configuration

- Type: ____________________
- Fully automated storage and retrieval system
- Electric drives:
  - x-axis: ____________________
  - y-axis: ____________________
  - z-axis: ____________________

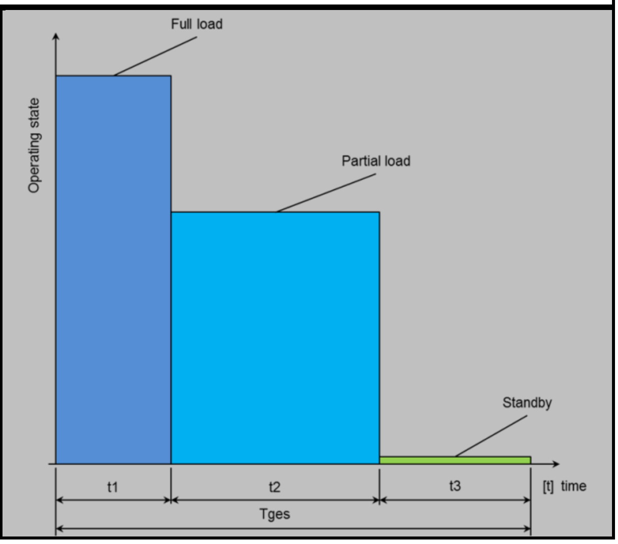
Technical data		
Carrying capacity		… kg
Rack length	l_{RM}	… mm
Rack height	h_{RM}	… mm
Width of aisle	b_{RM}	… mm
Storage space	nV	…
	nH	…
Racks/Aisle		…
		(bin compartments)
Horizontal bin distance within rack	t_x	… mm
Vertical bin distance within rack	t_y	… mm
Transshipping performance	λ	… DC/h
Acceleration	$a_x = a_y$	… m/s²
Velocity	v_x	… m/s
	v_y	... m/s

Further notes:
…

1.3 Representative operating cycle

1.3.1 Load spectrum

Load spectrum			
Operational state		Time slice $[t_i]$	% of carrying capacity
1	Full load	20%	90%
2	Partial load	60%	50%
3	Standby	20%	0%



Further notes:
...

1.4 Description of measurement process

Brief description of the task.
…

1.4.1 System boundaries

Insert a picture or drawing.
…

2 Measurement

2.1 Preparation

2.1.1 Measurement and sensor technology

Measurement devices, e.g. equipment, which is available at the Institute of Logistics Engineering.

- Benchtop laboratory instrument Dewetron DEWE-800
- A/D board Dewetron DEWE-ORION-1616-500
- 3x dynamic isolation amplifier modules Dewetron DAQP-HV (high voltage)
- 3x dynamic isolation amplifier modules Dewetron DAQP-LV (low voltage)
- 3x Current probe PROSYS CP300 AC/DC
- …

2.1.2 Machine setup & measuring instructions

Load spectrum					
Operational state		Time slice [t_i]	% of carrying capacity	velocity [v_{ix}] & [v_{iy}]	acceleration [a_{ix}] & [a_{iy}]
1	Full load	12 min	90%	100%	100%
2	Partial load	36 min	50%	100%	100%
3	Standby	12 min	0%	100%	100%
Time base				1 h	
Number of repetitions				5	
ROC according to the following procedure				e.g. according to FEM 9.851	

Further notes:
…

2.1.3 Loading

- Type of unit-load: ____
- Freight: ____

Operational state		**% of carrying capacity**	**Actual load/unit-load**
1	Full load	90%	22,5 kg/UL
2	Partial load	50%	12,5 kg/UL
3	Standby	0%	-

Further notes:
E.g. include some pictures
…

2.2 Implementation of measurement technology

2.2.1 Application of sensor technology

Include a wiring diagram here.
Include a list of measuring channels (Dewetron DEWE-800 incl. identification.
…

2.2.2 Initial operations

Operations that are to be done when using the measurement devices, e.g. equipment, which is available at the Institute of Logistics Engineering.
Description of each measurement process step:

- Switch on AS/RS and document time (warm-up phase)
- Turn on benchtop laboratory instrument Dewetron DEWE-800 PC
- Start DEWESoft Software
  - Check version and document number (most likely 7.0.4)
- Load setup file: ____
- Setup and calibrate measuring channel
  - Options
    - …
  - Analog
    - Reset current probes
    - …
  - Mathe
    - ...
- Adapt gauges to measurement that is to be performed (if necessary)
- Prepare loading
- Connect wiring (voltage) and probes (current) according to wiring diagram
  - Connect any sensor that is of interest
- Document setup and measurement series according to chapter 2.4
  - Adapt naming of data file when performing a measurement series (DEWESoft does not automatically adapt)
- Start recording
- Perform working cycle according to load spectrum
- Stop recording
- Check data file for error
  - Correction (if necessary)

Further notes:
…

2.3 Overview of planned series

	No loading m = 0kg	Partial loading m = 12,5kg	Full loading m = 22,5kg
Warm-up		-	-
Stand-by	-		
ROC (virtual or real)	-		
In/Output operation (z-axis only)	-		

Further notes:
…

2.4 Testing

2.4.1 Measurement Nr. XX - Warm-up phase

Name of data file:			
Date			
Time (period)			
Duration			
Type of measurement		☑ Electrical power consumption ☐ Cycle time ☐ Throughput	☐ rpm ☐ torque ☐ ☐
Operational state		☐ Full load ☐ Partial load	☐ Standby ☑ Warm-up
Performance data			
	Type of working cycle	☐ Single Cycle ☐ Double cycle	☑ None (Stand-By/Warm-up)
	Quantity		
	Execution according to	☐ Real ROC ☐ Virtual ROC	☐ Other ☑ Any
Reference points		Set value	Actual value
	File:	-	
	Available	☐ yes -> ok ☐ no -> perform with x/y-axis and z-axis separately Nr. of measurement belonging together:________________	
Position 1	P1x	-	
	P1y	-	
Position 2	P2x	-	
	P2y	-	
Cycle time			
	Position 1		
	Position 2		
Loading			
Environmental conditions			
	Temperature		
	Humidity		
Statistics			
Export			
Annotations			

2.4.2 Measurement Nr. XX - Standby

Name of data file:			
Date			
Time (period)			
Duration			
Type of measurement		☑ Electrical power consumption ☐ Cycle time ☐ Throughput	☐ rpm ☐ torque ☐ ☐
Operational state (Betriebszustand)		☐ Full load ☐ Partial load	☑ Standby ☐ Warm-up
Performance data			
	Type of working cycle	☐ Single Cycle ☐ Double cycle	☑ None (Stand-By/Warm-up)
	Quantity	-	
	Execution according to	☐ Real ROC ☐ Virtual ROC	☐ Other ☑ None
Reference points		Set value	Actual value
	File:	-	
Position 1	P1x	-	-
	P1y	-	-
Position 2	P2x	-	-
	P2y	-	-
Cycle time			
	Position 1	-	
	Position 2	-	
Loading (Beladung)		-	
Environmental conditions			
	Temperature		
	Humidity		
Statistics			
Export			
Annotations			

2.4.3 Measurement Nr. XX – Full load

Name of data file:			
Date			
Time (period)			
Duration			
Type of measurement		☑ Electrical power consumption ☑ Cycle time ☑ Throughput	☑ rpm ☑ torque ☐ ☐
Operational state (Betriebszustand)		☑ Full load ☐ Partial load	☐ Standby ☐ Warm-up
Performance data			
	Type of working cycle	☐ Single Cycle ☑ Double cycle	☐ None (Stand-By/Warm-up)
	Quantity	-	
	Execution according to	☐ Real ROC ☐ Virtual ROC	☐ Other ☐ None
Reference points		Set value	Actual value
	File	E.g. according to „RBG-Dimensionierung_ITL_v8.xlsm”	
	Available	☐ yes -> ok ☐ no -> perform with x/y-axis and z-axis separately Nr. of measurement belonging together:________________	
Position 1	P1x		
	P1y		
Position 2	P2x		
	P2y		
Cycle time			
	Position 1		
	Position 2		
Loading (Beladung)			
Environmental conditions			
	Temperature		
	Humidity		
Statistics			
Export			
Annotations			

2.4.4 Measurement Nr. XX – Partial load

Name of data file:			
Date			
Time (period)			
Duration			
Type of measurement		☑ Electrical power consumption ☑ Cycle time ☑ Throughput	☑ rpm ☑ torque ☐ ☐
Operational state (Betriebszustand)		☐ Full load ☑ Partial load	☐ Standby ☐ Warm-up
Performance data			
	Type of working cycle	☐ Single Cycle ☑ Double cycle	☐ None (Stand-By/Warm-up)
	Quantity	-	
	Execution according to	☐ Real ROC ☐ Virtual ROC	☐ Other ☐ None
Reference points		Set value	Actual value
	File	E.g. according to “RBG-Dimensionierung_ITL_v8.xlsm”	
	Available	☐ yes -> ok ☐ no -> perform with x/y-axis and z-axis separately Nr. of measurement belonging together:_________________	
Position 1	P1x		
	P1y		
Position 2	P2x		
	P2y		
Cycle time			
	Position 1		
	Position 2		
Loading (Beladung)			
Environmental conditions			
	Temperature		
	Humidity		
Statistics			
Export			
Annotations			

2.4.5 Measurement Nr. XX – __-axis only

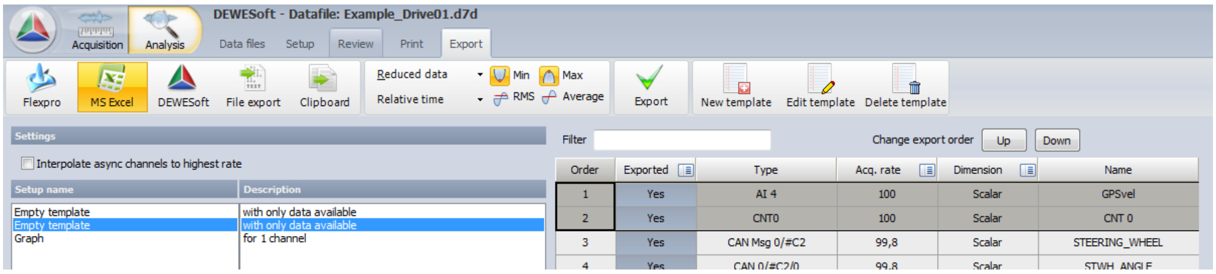
Name of data file:			
Date			
Time (period)			
Duration			
Type of measurement		☑ Electrical power consumption ☑ Cycle time ☑ Throughput	☑ rpm ☑ torque ☐ ☐
Operational state (Betriebszustand)		☐ Full load ☑ Partial load	☐ Standby ☐ Warm-up
Performance data			
	Type of working cycle	☐ Single Cycle ☐ Double cycle	☐ None (Stand-By/Warm-up)
	Quantity	-	
	Execution according to	☐ Real ROC ☐ Virtual ROC	☐ Other ☐ None
Reference point		Set value	Actual value
	File		
	Available	☐ yes -> ok ☐ no -> perform with x/y-axis and z-axis separately Nr. of measurement belonging together:________________	
Position 1	P1x	-	
	P1y	-	
Position 2	P2x	-	
	P2y	-	
Cycle time			
	Position 1		
	Position 2		
Loading (Beladung)			
Environmental conditions			
	Temperature		
	Humidity		
Statistics			
Export			
Annotations			

3 Analysis

3.1 Data Export

Measurement devices, e.g. equipment, which is available at the Institute of Logistics Engineering.
Description of each analysis process step:

- Start DEWESoft Software (version does not necessarily have to be the same as installed on benchtop PC)
- Select desired measurement range
- Export data to MS Excel
    - Select 2nd empty template in DEWESoft
    - Select desired measurement channels (max. 2 due to limitations of MS Excel evaluation file)
    - Setup:
        - “Reduced data”
        - “Relative or absolute time”
        - Select “Min”, “Max”, “RMS”, “Average” accordingly
- Run MS Excel evaluation file:______________________________________
    - Version of evaluation file: ______________________________________



- Run MS Excel evaluation file:______________________________________
    - Version of evaluation file: ______________________________________

3.2 Data Analysis

Measurement Nr.	**Number of measurement**
Name of data file:	Filename and
Storage location of file	
Annotations	

Insert diagram here…
Further notes:
…

Measured data	
Name of channel	
Unit	
Count	
Mean	
SD	
Min	
Q1	
Median	
Q3	
Max	

3.3 Calculation and results

Calculation according to chosen energy efficiency indicator.

3.4 Findings

Describe the findings.