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Performance Analysis of Shuttle-Systems

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Abstract

In this thesis a tool is developed to simulate a tier captive shuttle system with one aisle. In order to develop the tool a simulation study was carried out. The outcome of the simulation study is a software model which is implemented in Excel- Visual Basic for Applications (VBA). In this tool, the shuttle system can be configured in various ways. The kinematic parameters for lift and shuttle can be adjusted and certain storage strategies can be applied. Additionally, the functions can be evaluated within the tool. After a simulation run, the tool provides detailed information about the shuttle system e.g. system throughput, utilization of the elements and additional statistics.
Thus the tool can support the planning and design of a shuttle system. With the detailed information from the simulation, deeper insights in the system can be gained and conclusions on the real system can be drawn.

Kurzfassung

In dieser Arbeit wurde ein Tool entwickelt, dass ein ebenen-gebundenes Shuttle System mit einer Gasse simuliert. Es wurde eine Simulationsstudie durchgeführt, um ein Software Modell zu erstellen. Aus dem Ergebnis dieser Studie wurde ein Softwaremodel entwickelt, das in Excel Visual Basic for Application (VBA) realisiert ist. Mit diesem Tool kann in vielfältiger Weise durch Konfigurationsabänderungen das Shuttle Systems variiert werden. Der Benutzer des Tools kann unterschiedlichste Einstellungen für die Simulation treffen. Es können die kinematischen Parameter für Lift und Shuttles abgeändert werden und auch unterschiedliche Lagerstrategien ausgewählt werden. Des weiteren, können die internen Funktionen im Tool verifiziert werden. Nach einem Simulation Durchgang, stellt das Tool Informationen über das Shuttle System bereit. Diese beinhalten z.B. den Systemdurchsatz, die Auslastung der einzelnen Element oder auch zusätzliche Systemstatistiken. Somit kann das Tool die Planungs- und Entwicklungsphase eines Shuttle Systems unterstützen. Mit den gewonnen Informationen aus der Simulation können tiefere Einblicke und Schlüsse auf das reale System gezogen werden.

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1 Introduction

For global supply chains the material handling is a growing and vital concern, especially the storage and retrieval systems for unit loads. [EKR11] Since the 1950s crane-base automated storage and retrieval systems (AS/RS) are common used in production and distribution environments [RV09]. On the one side AS/RS provides high throughput rates and high storage density but on the other side they are also expensive. The autonomous vehicle technologies for unit load storage and retrieval systems (AVS/RS) are an alternative technology for AS/RS. They can also reduce the scale of cost efficiency. [KKM07] Such an AVS/RS consists of storage rack, lifts, rail systems and rail guided autonomous vehicles (AVs). The autonomous vehicles are using the rail systems to reach any location on the same vertical level (Figure 1-1) [EKR11].
It has to be distinguished between autonomous vehicles, which are always on the same vertical level, i.e. the same tier in the rack and vehicles which are changing their vertical position. In this case they are able to move from one tier to another tier in the rack by the means of the lift. The first configuration is called 'tier captive' and the second is called 'tier to tier' configuration.

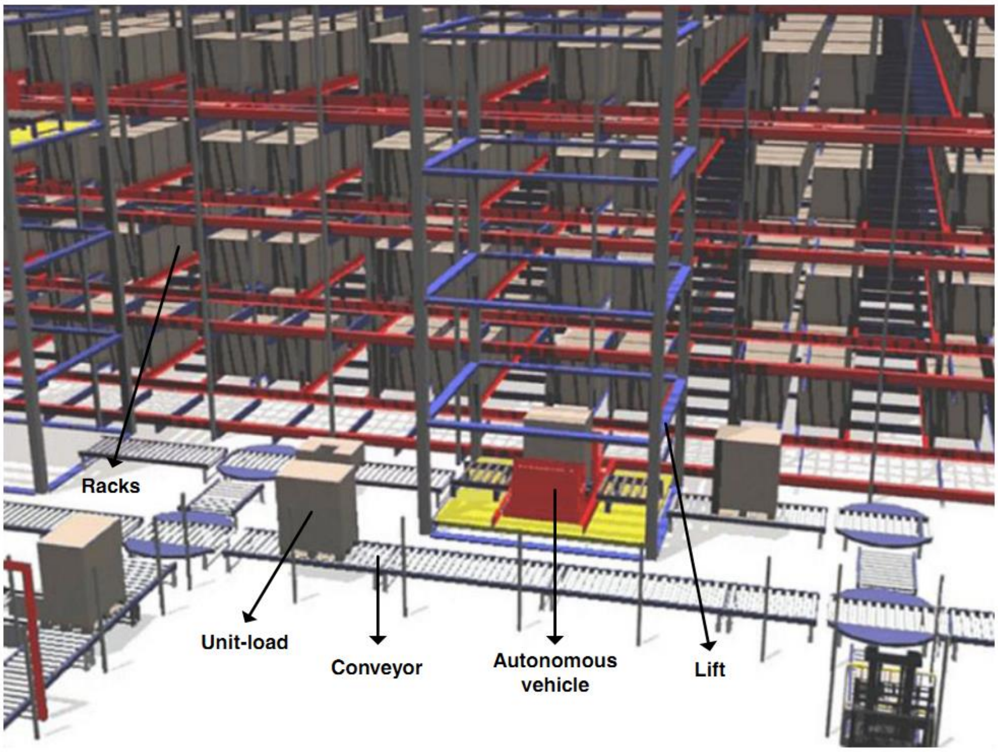

Figure 1-1: Components of an AVS/RS [EKR11]

To achieve that the lift and the autonomous vehicles can move independent, in each tier a buffer for storing and a buffer for retrieving is maintained at the front site of the rack. The buffer for handling the retrieval orders is called 'buffer out' and the buffer for handling the storage orders is called 'buffer in' (Figure 1-2). [MMP12+]

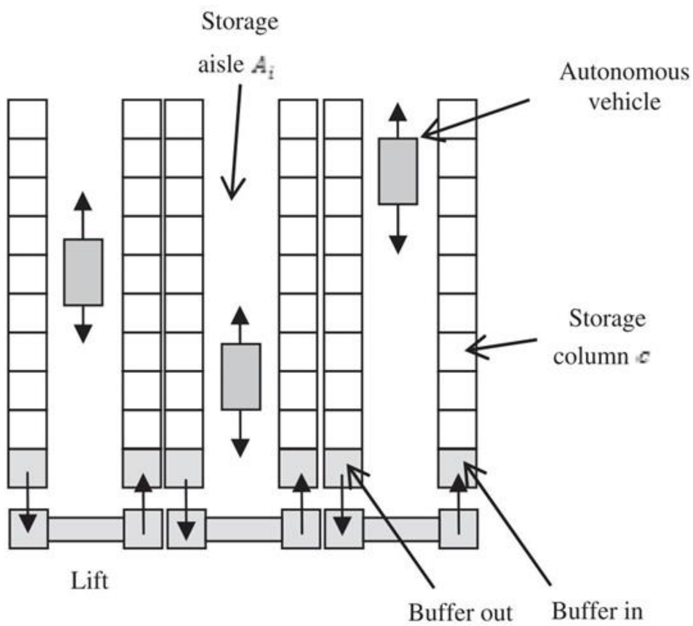

Figure 1-2: AVS/RS with 'tier captive' configuration [MMP12+]

By changing the number of autonomous vehicles it is possible to adopt the system throughput capacity. For example by decreasing the number of vehicles also the warehouse throughput capacity decreases. This adaptability of system throughput capacity is a big advantage and it can provide cost-effective automation. [EKR11]
The physical layout and the equipment of AVS/RSs are quite inflexible for changes. Therefor it is important to design the system right in the first time. This means the system shall avoid bottlenecks and overcapacity. [EKR11]

The aim of this thesis is to develop a tool to support the planning process of an AVS/RS. Hence such AVS/RSs are investigated to derive measures for supporting the planning phase. Figure 1-3 illustrates methods for investigating a system. Experimenting on the real AVS/RS was neither possible nor necessary for this thesis. So a simulation of an AVS/RS was carried out. The Institute of Logistics Engineering of the Technical University of Graz has already developed a simulation model to analyze AVS/RSs. This simulation is developed in Excel-VBA and uses the Monte-Carlo method. Thus the base for this thesis was set. In the course of this thesis, the existing simulation model has been modified and extended in various ways.

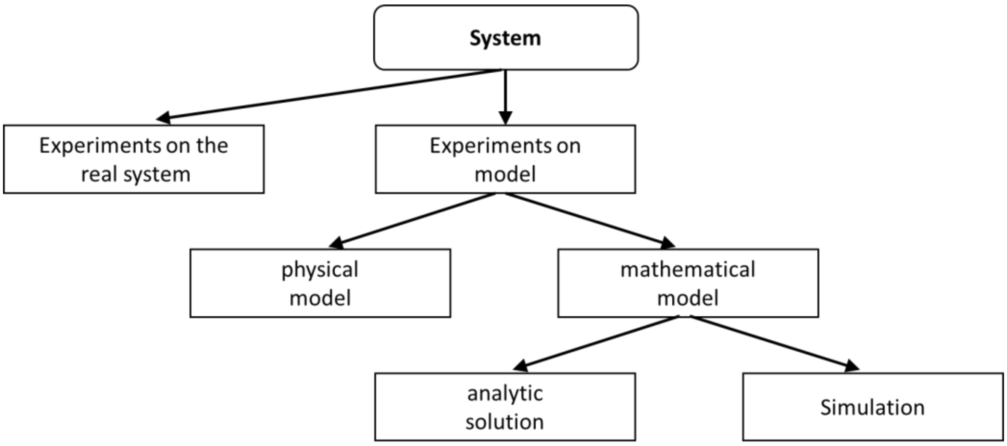

Figure 1-3: Methods for system investigation [GH10]

2 Problem analysis

In this chapter the basic theory for this thesis is examined. It is grouped in four parts. First, the basic logistics coherences are briefly described. Second, the goodness-of-fit tests are examined. Third, the term simulation is discussed and fourth the procedure of a simulation study is examined.

2.1 Logistics

In this section the throughput calculation for conveyor lines and the velocity-time behavior of a conveying unit is examined. Additional the ABC- strategy is highlighted.

2.1.1 Throughput calculation

Conveyor units are moving on the conveyor line with the velocity v from the source (Q) to the drain (S) (Figure 2-1). Thereby, it is imagined that the source is creating the conveyor units although it is not their real point of origin. For the throughput calculation it is important to know the velocity-time-behavior of the conveyor unit. Thus, the throughput of a conveyor line can be calculated with the velocity v and the distance s to the following conveyor unit (Equation 2-1). [ArF09]

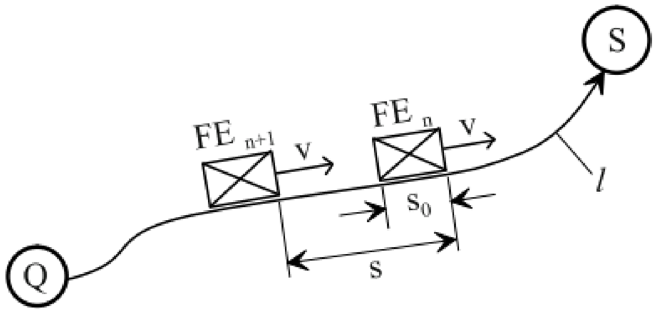

Figure 2-1: Conveyor line [ArF09]

$$\lambda = \frac{v}{s} \qquad \left[\frac{1}{Time\ unit}\right]$$

Equation 2-1: Throughput calculation [ArF09]

2.1.2 Velocity- time behavior

The velocity-time behavior of a conveying unit is displayed in Figure 2-2. This trapezoid curve composes of three phases.

- start-up phase, where the unit accelerates to its maximum velocity v_{max}
- steady state, where the unit moves with constant velocity v_{max}
- brake phase, in which the unit decelerates until it stops.

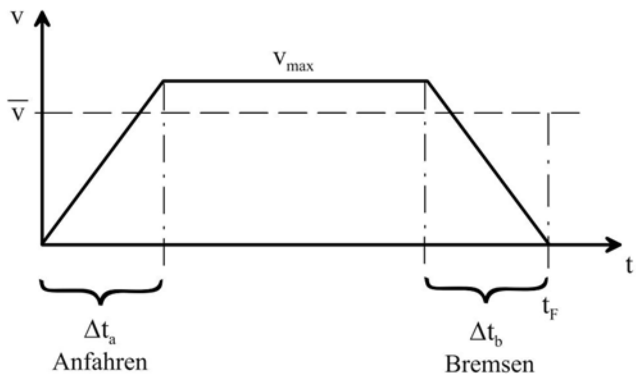

Figure 2-2: Velocity-time behaviour for conveying units [ArF09]

If the distance to accelerate to the maximum velocity is too short, the velocity-time behavior is triangular (Figure 2-3). The equation to calculate the travel time is shown in Equation 2-2. Thereby, s is the distance between start and stop, and *a* the average mean acceleration-deceleration-constant and calculated with the acceleration and deceleration (Equation 2-3).
When the velocity-time behavior of the conveyor unit is a trapezoid curve, the travel time is calculated as shown in Equation 2-4.

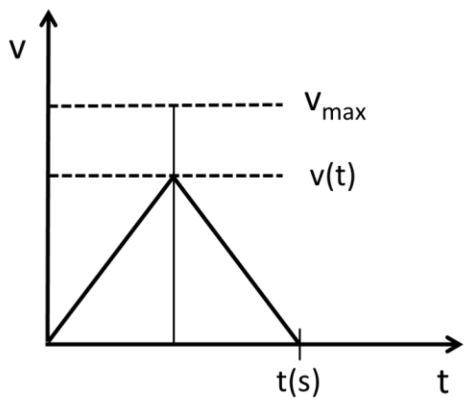

Figure 2-3: Triangular movement of a conveyor unit

$$t(s) = 2 * \sqrt{\frac{s}{a}} \qquad \text{for} \qquad s \geq \frac{v_{max}^2}{a}$$

Equation 2-2: Travel time for triangular behaviour [GUD12]

$$a = \frac{2 * a^+ * a^-}{a^+ + a^-}$$

Equation 2-3: Acceleration-deceleration-constant [GUD12]

$$t(s) = \frac{s}{v_{max}} + \frac{v_{max}}{a} \qquad \text{for} \qquad s < \frac{v_{max}^2}{a}$$

Equation 2-4: Travel time for trapezoid behaviour [GUD12]

2.1.3 ABC-strategy

ABC-goods are classified according to certain criteria. This can be the turnover rate, quantity of sales or the access frequency. A-goods have a high turnover rate, quantity of sales or access frequency. C-goods only have few turnover rates, quantities of sales or access frequencies. When these criteria are sorted according to their incidence, the so called Lorenz-curve occurs (Figure 2-4). [VtH06]
The throughput of a rack can be increased by storing the goods with a high access frequency near the output position. Thus the transportation ways are decreased, which leads to reduced cycle times. Therefor ABC-distribution is used when for instance 20% of the goods have an overall access frequency of 80%. [Ar08]

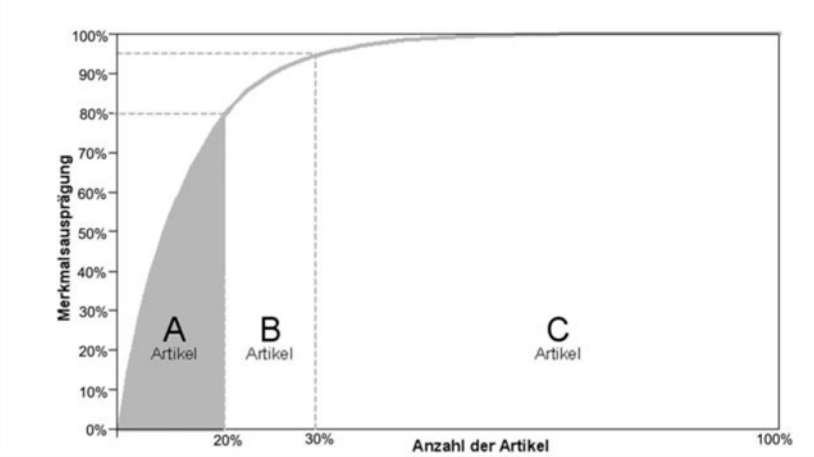

Figure 2-4: ABC-distribution, Lorenz-curve [VtH06]

2.2 Goodness-of-fit tests

The goodness-of-fit tests are used to verify if the data is corresponding to a certain distribution.
In statistics it is often assumed that the data is corresponding to a certain theoretical distribution. Within a goodness-of-fit test, the empirical distribution is compared with the theoretical distribution. If the deviations are too high, it can be supposed that the data is not corresponding to the assumed distribution. [DUL08] In the following section two kinds of goodness-of-fit tests are described: the Chi-square test and the Anderson-Darling test.

2.2.1 Chi-square test (χ^2-test)

The Chi-square test can be used to test the stochastic independence or dependence of characteristics or it can be used as a goodness-of-fit test. In this case it is tested if the observed frequencies derive significant from the expected frequencies. The quality of the Chi-square test is not very high compared to other goodness-of-fit tests, because the data has to be grouped in classes. This grouping can influence the result. [DUL08]

χ^2-test for goodness-of-fit

Hypotheses
$H_0: \chi^2 = 0$ *The distribution corresponds to the theoretical distribution*
$H_1: \chi^2 > 0$ *The distribution does not correspond to the theoretical distribution*

Decision rule
Equation 2-5 shows the Chi-square test value, where h_E is the expected frequency and h_i the empirical/observed frequency. The null hypothesis is rejected when the test value is bigger than the (1-α)-Quantile of the Chi-square distribution. [DUL08]

$$\chi^2 = \sum_{i=1}^{n} \frac{(h_i - h_E)^2}{h_E}$$

Equation 2-5: Chi-square test value [DUL08]

Critical value
The critical value is the (1-α)-Quantile of the Chi-square distribution: $\chi^2_{r-k-1,1-\alpha}$
Where r the number of classes (categories) is, α the significance level and k is the number of the estimated parameters. For a discrete uniform distribution is k = 0. [DUL08]

2.2.2 Anderson-Darling test

The Anderson-Darling test is only valid for certain distributions (e.g. normal distribution, Weibull distribution, exponential distribution) [DUL08].
To test for normal distribution, the distribution of the measured values is arithmetical verified if they fit to a normal distribution. This arithmetical verification is similar to a graphical verification and uses a probability plot. [BRE15]

Hypotheses
$H_0: F(x) = F_0(x)$
$H_1: F(x) \neq F_0(x)$

Decision rule
The decision rule for the Anderson-Darling test is shown in Equation 2-6. The null hypothesis is rejected when the test statistic (Equation 2-7) is bigger or equals the critical value [DUL08].

$$AD^2 \geq AD^2_{n,1-\alpha}$$

Equation 2-6: Decision rule for the Anderson-Darling test [DUL08]

Test statistic

$$AD^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\left[\ln\left(F_0(x_i)\right) + \ln(1 - F_0(x_{n-i+1}))\right]$$

Equation 2-7: Practical calculation for the test statistic [DUL08]

Critical value

The critical value $AD^2_{n,1-\alpha}$ can be obtained from tables (Table 2-1) or calculated by itself. Equation 2-8 illustrates the critical value for a normal distribution with the confidence level α=0.05. In this equation is n the sample size. [DUL08]

n	1	2	3	4	5	6	7	8	$n \to \infty$
$1-\alpha = 0.90$	2.05	1.98	1.97	1.95	1.94	1.95	1.94	1.94	1.933
$1-\alpha = 0.95$	2.71	2.60	2.55	2.53	2.53	2.52	2.52	2.52	2.492
$1-\alpha = 0.99$	4.30	4.10	4.00	4.00	3.95	3.95	3.95	3.95	3.857

Table 2-1: Critical values for complete specified normal distribution [DUL08]

$$AD^2_{\mathrm{n},0.95} = \frac{0.752}{1 + \frac{3}{4n} + \frac{9}{4n^2}}$$

Equation 2-8: Critical value for α=0.05 [DUL08]

2.3 Simulation

Simulation is defined as a problem solving method. With this method complex, dynamic factual connections can be analyzed. Statements about the temporal behavior of a system can be gained with models. Important simulation characteristics are the ability to display randomness, modeling of time, systematic parameter variation and the reproducibility of results. [BGW11]
A model is an abstraction and simplification of the reality. The model is created by the means of scientific methods. [ArF09]
The main aim of a simulation is to get simulation results. The results can be qualitative or quantitative and are used to evaluate the research subject. [RSW08].
It has to be mentioned that, a simulation does not result in exact and optimal values. A simulation is a heuristic, statistically estimation technique which uses random samples. This has to be kept in mind when testing and comparing with alternative material flow concepts. [ArF09]

2.3.1 Simulation methods

It can be distinguished between three kinds of simulation methods: The continuous, the time-controlled and the discrete event simulation. For the continuous simulation the time and the state variables can be expressed by continuous functions (e.g. FEM, CFD). For the time-controlled simulation the simulation

time is increased with a fixed time value after each simulation step (e.g. substances-, energy flow, economical investigations).
During a discrete event simulation (DES) a change of state can only occur on a discrete time in dependence of an event. These events trigger the change of state. The events, which have to be fulfilled, are administered in an event log with a timestamp. The events are carried out in ascending order according to their timestamp. Thus, systems with discrete moveable objects can be created (e.g. material flow- or production systems). [BGW11] For the DES the sequence of states is discontinuous and stochastic [ArF09].
In this thesis the discrete event simulation is used to model a shuttle system.

2.3.1.1 Monte-Carlo-Method

The Monte-Carlo-Method is a stochastic computer simulation [RuK07]. The name Monte-Carlo was given by John von Neumann. Together with Enrico Fermi and Stanislaw Ulam, Neumann worked on a secret project; the Manhattan Project, which led to the Atomic bomb. For this they simulated the movements of neutrons by a stochastic computer simulation, later called the Monte-Carlo-Method.
The central terms of the usage of the Monte-Carlo-Method are modelling and process simulation. [Nah15]
Nowadays the Monte-Carlo-Method is wide spread. It is used for optimizing processes or for the determination of distribution attributes. Furthermore weather and climate models can be created or problems within a production process can be revealed with the Monte-Carlo-Method. The method is also used in the field of mathematics to determine the Circle Constant π. [Nah15]
For the Monte-Carlo simulation the random numbers are very important. Therefore, the computer has to generate random numbers. The problem with generating random numbers by a computer is that the machine is deterministic. For this reason it is not possible to create real random numbers. It is only creating so called Pseudo-Random numbers. This Pseudo-Random numbers have similar attributes like real random numbers. There is no guarantee, that the usage of Pseudo-Random numbers delivers correct results. Nevertheless their usage is vitally important and very efficient. [Nah15]
Hereafter, for the reasons of simplicity, it will be only spoken of random numbers and not of Pseudo-Random numbers even if all the random numbers in this simulation are actually Pseudo-Random numbers.

2.3.1.2 Convergence criterion

For a stochastic process the convergence criterion can be determined by constructing a valid confidence interval for the expected value. The expected value of the stochastic process must have the property given in Equation 2-9. Thus statistically valid confidence intervals can be created. x_i is the simulation sample. [Ata07]

$$\lim_{n\to\infty}\left(\bar{x}_n = \frac{1}{n}\sum_{i=1}^{n} x_i\right) \overset{w.p.1}{\Longrightarrow} \mu \qquad \text{with} \qquad x_i: i = 1(1)n$$

Equation 2-9: Valid confidence interval [Ata07]

A proposed convergence criterion for the Monte-Carlo-Method seeks a convergence band of a given width and length. The sample mean values must be within the borders of the convergence band. The convergence criterion for the Monte-Carlo-Method can also be used as stopping criterion for the number of simulation runs. [Ata07]

2.3.2 Random number generator

All the state changes in a deterministic system are processing according to plan. The same input values always results in the same predictable output values. If there is only one random variable, the system will be a stochastic system. The same input values are now resulting into different, random output values. [ArF09]
Therefore for a simulation study it is very important to generate random numbers. These numbers are generated with a so called random number generator. With the same starting value (seed value) the generator must always be able to reproduce the identical set of random numbers. This set of random number must have a long series before repeating. [BAR06+]
In this thesis the Excel-VBA random number generator is used. The algorithm is shown in Equation 2-10. In this equation x_1 is the new value, x_0 the previous value (an initial value of 327.680 is used by Visual Basic), while a and c have a constant value of 1.140.671.485 and 12.820.163.

$$x1 = (x0 * a + c)MOD(2^{24})$$

Equation 2-10: VBA-Rnd() algorithm [MC16a]

The 'MOD' operator in the Equation 2-10 returns the integer remainder after an integer division. The expression $x_1/2^{24}$will return a floating-point number between 0.0 and 1.0, which is returned by the RND function. [MC16a]

2.4 Simulation study

In this chapter the theoretical procedure to develop the tool is emphasized.
This procedure is called simulation study. A simulation study consists of different phases (Figure 2-5). These phases are interlinked with each other and cannot be separated clearly. Furthermore, each phase is repeated iteratively before the next phase can be carried out. In literature, the phases within a simulation

study are different structured and assigned [KUH06]. But almost all simulation studies imply the phases:

- Task analysis
- Model design
- Model implementation
- Model review
- Model application [RSW08]

In the following the phases according to Kühn (2006) are briefly described.

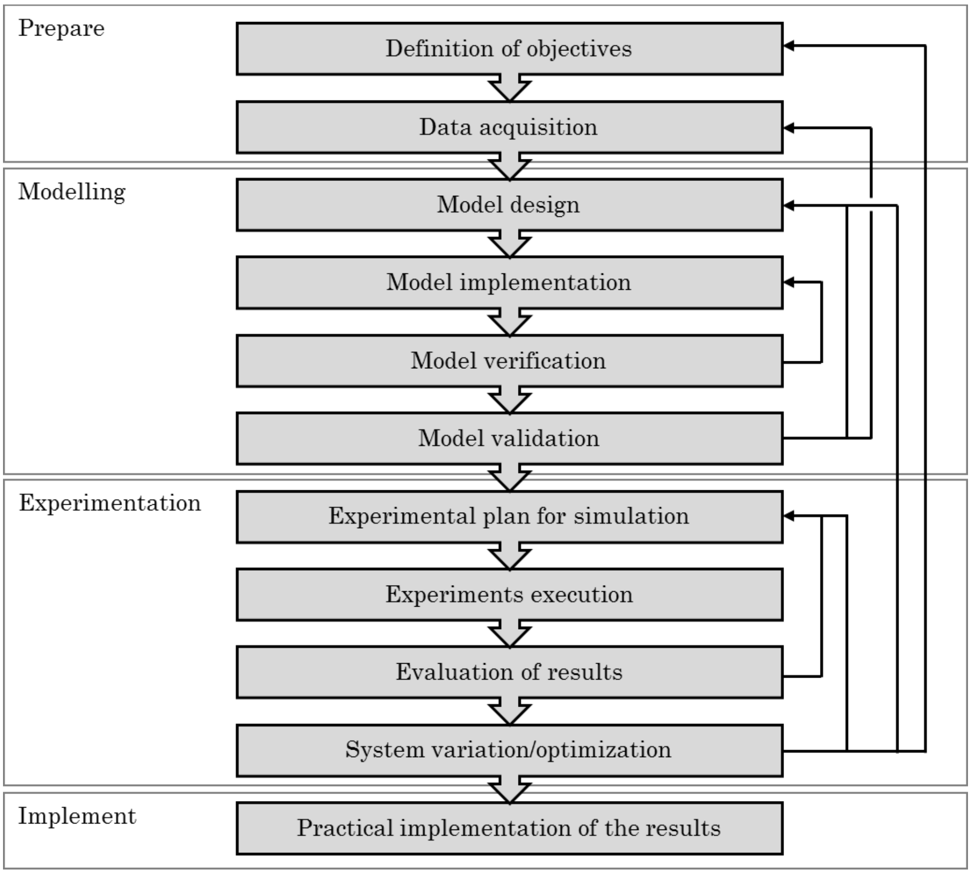

Figure 2-5: Simulation study procedure [KUH06]

2.4.1 Definition of objectives

In this phase, the objectives for simulation are defined. These objectives have to be specified very clearly. Within the objectives definition, the effort effectiveness relationship has to be kept in mind. Be careful, because the effort to gather the data, modelling and simulation is reasonable to achieve the objectives. The analysed system, within the simulation, must have a defined border to the environment [KUH06].

2.4.2 Data acquisition

The simulation results are only as good as the input data (Garbage-In Garbage-Out). The data acquisition and preparation is therefore very important. Thereby the plausibility and the correctness of the data have to be checked. The modelling process and the data acquisition are in close interaction [KUH06].

2.4.3 Model design

The model design leads to a conceptual model. In this model, the boundary to the environment is specified. Afterwards, the logical model is designed. Which represents the structure and the material flow of the initial system and can be shown as a flow chart or block diagram [GH10].
In the conceptual model the relevant system interactions have to be implemented. It is not possible or desired to model the system with its complete complexity. The effort to build the model is defined by its level of detail and the system complexity. The level of detail for the simulation has to be kept in mind in order to gain detailed results in an acceptable processing time. A clear definition of objectives is important for the model design. Furthermore, for the model, it has to be considered which input data is set, which scenarios shall be displayed and the boundary values for the model (Figure 2-6).
Independent sub models are easy to manage and to validate. Changes within the models are also easy implemented. But these sub models may have a lack of interconnections. Thus these sub models may not exact correspond to the system which has to be build.
An overall model displays the system more accurate because more detailed interconnections are implemented. However such overall models are very complex, the troubleshooting is difficult and there is a long processing time [KUH06].

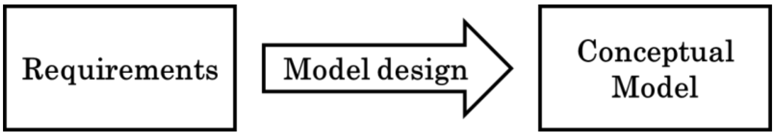

Figure 2-6: Model design [KUH06]

2.4.4 Model implementation

There are different ways to implement the model: parameterization of software modules, specification of networks or programming with a simulation language. For the implementation it is also necessary to document the source code (Figure 2-7). After the implementation the software model has to be checked. Syntax check is normally done by the modelling system itself. The logical review is done by the verification and validation [KUH06].

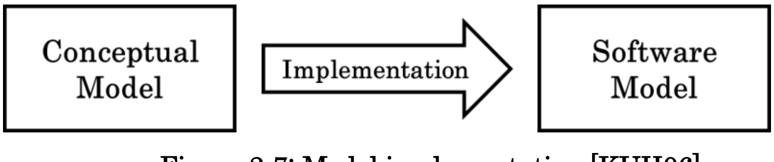

Figure 2-7: Model implementation [KUH06].

2.4.5 Model verification

In model verification phase, it is verified if the logical functions within the software model are implemented correctly and if the software model represents the conceptual model. The result of the verification is a model which represents logical correct the conceptual model (Figure 2-8). Verification and Validation are main components of a simulation study. They should be carried out not only at the end of the study but also during the simulation study. [KUH06]

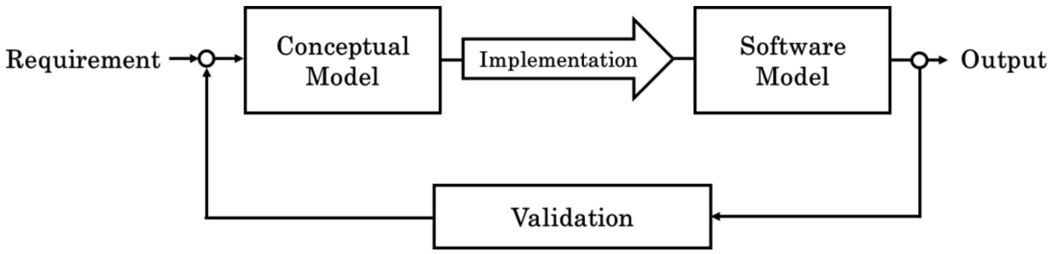

Figure 2-8: Model verification [KUH06]

Therefore verification and validation of the simulation is done to avoid incorrect results which lead to wrong conclusions. In literature a variety of verification and validation techniques are mentioned and which are named and described differently [RSW08]. The used verification and validation techniques are described in the following section.

2.4.5.1 Animation

With an animation the chronological event sequence can be displayed two- or three- dimensional. Hence it can be monitored if the sequences in the model are valid or if there are any differences to the real system. During an animation only a certain period of time is observed, therefore a conclusion to the real system beyond this time period is not possible. To review the behaviour of the model during a certain period of time is also the main strength of the animation. [RSW08]. The quality of the animation does not indicate to the quality and correctness of the simulation model. [KUH06]

Animation can be useful for:

- Validation, with the aim to show the system behaviour in a transparent way.
- To focus on certain parts of the model and to test them.
- To display significant events in a reasonable speed. [RSW08]

2.4.5.2 Dimensional consistency test

The dimensional consistency test is used to reveal conceptual errors during the development of equations. Due to the check of the dimensions on both sides of the equation, inconsistencies inside the equation and in the allocation to a value can be revealed. [RSW08]

2.4.5.3 Sub model testing

During the development of the software model, sub models can be verified and validated before they are merged to the complete model. Therefore the sub models have to be expanded by a special test frame. The verification and validation of all sub models does not replace the verification and validation of the complete model. The test of sub models is only applicable if the model is structured hierarchical and the decomposition of the model can be compared with the real system. It is reviewed if the sub models are corresponding to the components of the real system. [RSW08]

2.4.5.4 Trace analysis

With the trace analysis, single objects in the software model are persuaded to check the logical behaviour and the validity. A trace consists of several data records. This data records include information from the model like the identification number, time, class object, location of the object, status etc. For the trace analysis it might be useful to use extreme conditions of the model or to use deterministic input data. Thus the trace can be reviewed by recalculating it by hand. [RSW08]

Verification in general

There is no general procedure to choose an appropriate verification and validation technique.
All these techniques are only used to exclude errors. When the software model does not have any errors, the model has a higher credibility. The model is credible when the null hypothesis cannot be rejected. The null hypothesis states that the model and the reality are corresponding sufficiently according to the task formulation. To improve the effectiveness of these single techniques, multiple techniques can be combined. Another aspect to be keep in mind, are the actions during the verification and validation are subjective. Hence they have to be critically reviewed and questioned.
The demonstration of the complete correctness of a model is formal not possible. It has to be decided subjectively which functions are necessary to verify and which functions are not necessary to verify. Consequently there is no evidence of the objective validity of the model. [RSW08]

2.4.6 Model validation

During the validation phase it is checked if the implemented software model corresponds to the real system and if the software model meets the requirements. The validation phase is more complex than the verification phase. It is an iterative testing and correcting process for modeling. The implemented software model has to represent the real model sufficient accurate. Furthermore the investigated system behavior has to be displayed correctly (Figure 2-9).
The review for the software model is for each project individual. There are no exact rules for the steps during the review. Depending on the software study

different analysis according to the target values, basic parameters and the plausibility check are carried out. [KUH06]

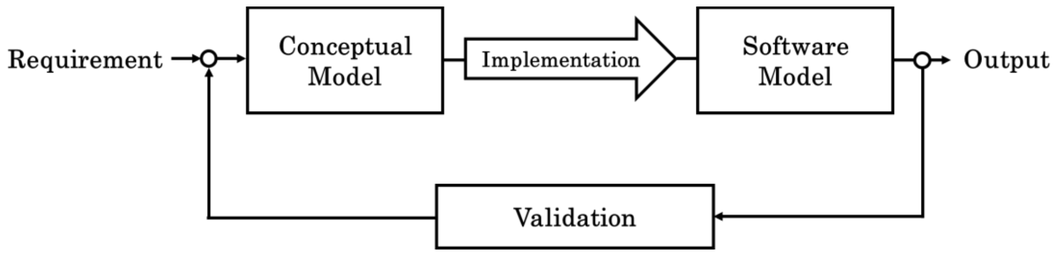

Figure 2-9: Model validation [KUH06].

In order to check the validity of a software model several different techniques can be used [RSW08]. One possibility to check the internal validity of the software model is to repeat a simulation run multiple times. Is there a large scattering within the results, it can be said that the model is not corresponding to the real system. Therefore several simulation runs with the same random number should be carried out. [ArF09]

2.4.7 Experimental plan for simulation

After the development of the software model, simulation runs are carried out. Thereby useful series of experiments with different parameters are executed. This specific analysis is also called simulation experiment. [GH10] A simulation experiment consists of several steps and it is used to investigate the model behavior (Figure 2-10). During the simulation experiment it is neither possible nor useful to cover all the possible parameter combinations. It is better to carry out a series of experiments with a precise variation of specific parameters. The parameters must be chosen reasonable because the effort is high to execute the simulation runs and to evaluate the results. [KUH06]

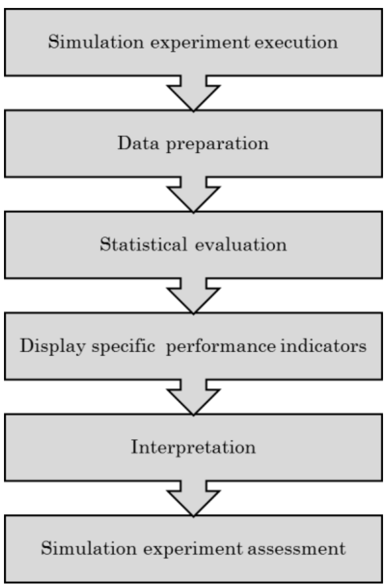

Figure 2-10: Steps within a simulation experiment [KUH06]

2.4.8 Experiments execution

Based on the experimental plan for simulation, the necessary simulation runs are carried out. The execution of the experiments is in the most instances very complex and the number of influence factors is very high. [KUH06]

2.4.9 Evaluation of results

The data, which is gained from the experiments, has to be prepared, condensed, and interpreted. Therefore conclusions can be drawn to the real system. [GH10]
Also single components can be analyzed, like puffer- or conveying elements and different simulation runs with varying simulation parameters can be compared [KUH06].

2.4.10 System variation/optimization

In this phase the system behaviour of the software model is corrected or optimized. Therfore the previously phases have to be carried out again. The phases are iterativ repeated until the desired system behavior of the software model is achieved.

2.4.11 Practical implementation of the results

With the results of the simulation, a conclusion to the real system can be drawn. The correct functionality of the system can be shown or a iterative optimzed control strategy can be developed. Furthermore it can be revealed if there are some missing functions in specific scenarios. [KUH06]
With the results of the simulation also recommendation for actions can be contrived. This recommendations have influence on the dcisions in the reality. Therfore the credibiltiy of the complete software model is important for the credibility of the results. [RSW08]

3 Development of measures

In this chapter the requirements for the tool ‘Shuttle analysis’ are emphasized. The tool has to be capable of several functions. By ‘shuttles’ the autonomous vehicles within an AVS/RS are meant. The tool simulates an AVS/RS with one aisle and different storage strategies. The main aim is to get performance data and other significant information about the elements (lifts, shuttles etc.) of the AVS/RS.
In order to simulate the AVS/RS a discrete event simulation is carried out with the use of the Monte-Carlo-Method. A change in the AVS/RS system is always discrete, e.g. the number of boxes stored into the rack.
The Monte-Carlo-Method is used to simulate the randomness of which box has to be stored or retrieved. That means that a random number generator (chapter 2.3.2) is used to generate the boxes and thus which actions have to be fulfilled within the system. These boxes are created uniformly. To archive sufficiently correct results from the simulation, a large number of actions within one simulation run have to be carried out. The reason for this is the law of large numbers.
It says if there are sufficient many random numbers for an interval, the probability will be higher that on this interval the random numbers are uniform distributed [Nah15].

The Institute of Logistics Engineering at the TU Graz has already developed a AVS/RS simulation. It is developed in Excel- Visual Basic for Applications (VBA). In this simulation the system only performs retrieval actions.
The most critical actions are the retrieval actions because they cannot be postponed to a low-workload phase. After the retrieval actions are modelled, it is easier to expand the simulation and implement storage actions. [MMP12+]
This existing tool was the base of operation for this thesis. The aim is to expand the tool with regard to system design flexibility, storage strategies and detailed insights of system performance. The detailed functions for the tool are discussed in the following.

3.1 Shuttle analysis functions

The existing tool has to be extended by various functions; an overview is shown in Table 3-1. They are divided in four main parts. The functions within the ‘system configuration’ are used to configure the system (i.e. the aisle with the rack, shuttles and lifts). The ‘storage strategies’ functions define the strategies for the rack occupancy and the handling of the moveable unit. The functions for ‘performance data’ deliver detailed insight information of the system. The last part is the ‘internal calculation functions’, these functions are needed for the internal operations of the tool.
After the implementation of the functions, it has to be checked if the functions are processed correctly. This verification of the single functions and combinations is executed in chapter 4.4.

1. System configuration	2. Storage strategies	3. Performance data	4. Internal calculation functions
1.1 Kinematic parameters for shuttle and lift	2.1 Shuttle buffer position	3.1 Throughput calculation	4.1 Calculate distance
1.2 Rack dimensions	2.2 Lift strategies	3.2 Lift utilization	4.2 Calculate travel time
1.3 Bay dimensions	2.2.1 Load carrier capacity	3.3 Shuttle utilization	4.3 Loading time shuttle
1.4 Cycle times	2.2.2 Number of lifts per aisle	3.4 Tracking of specific boxes	4.4 Loading time lift
1.5 Dead times	2.2.2.1 Lift strategies for two lifts per aisle	3.5 Display occupied rack	4.5 Shuttle find empty bay
	2.3 Lift input position	3.6 Display fulfilled order list	4.6 Relocation of a box
	2.4 Lift output position	3.7 Display fulfilled random orders	
	2.5 Buffer capacity	3.8 Display ABC distribution	
	2.6 Storage sequence	3.9 Display event list	
	2.7 Degree of rack filling	3.10 Display batch size	
	2.8 Rack occupancy strategies	3.11 Additional statistics	
	2.8.1 Random rack occupancy	3.11.1 Mean cycle time	
	2.8.2 Rack occupancy from behind	3.11.2 Mean relocation time	
	2.8.3 Occupy with occupation list	3.11.3 Mean waiting time	
	2.8.4 Occupy through storage process	3.11.4 Mean waiting time in buffer	
	2.9 Parameter variation	3.11.5 Mean waiting time for free buffer	
	2.10 ABC-distribution	3.11.6 Amount retrieved boxes	
	2.11 Order list	3.11.7 Amount stored boxes	
	2.12 Order Sequencing	3.11.8 Mean relocation cycles	
	2.13 'Real' random numbers	3.11.9 Buffer utilization	
		3.12 Examine convergence	
		3.13 Display random numbers	
		3.14 Quality of rack occupation	
		3.15 Quality of order creation	

Table 3-1 Shuttle analysis functions

3.2 Term explanation

To describe the functions, some specific terms are used. These are explained in the following section.

Box

A box is a moveable unit. It is defined by a unique name ("Box" and a consecutive number), the location in the rack (i.e. tier, column and the depth position) and the action which defines the activity for this box. There are two possible actions for a box, the 'retrieving' and the 'storing' action. When the box is located in the rack, the action of this box is "retrieving". It means the box has to be retrieved from the rack. When the box is outside the system (aisle), the box action is "storing". Thus, the box has to be stored into the rack.

Input-position (abbr.: I-position)

Interface between the aisle and the outside world. At this position boxes, get into the aisle.

Output-position (abbr.: O-position)

Interface between the aisle and the outside world. At this position, boxes get out of the aisle.

Input/Output-position (abbr.: I/O-position)

It is a combination of the input and output position. At this position boxes can get into the aisle and out of the aisle.

Orders

The orders are tasks which have to be fulfilled. An order is represented by a box. Either the box has to be stored into the rack or retrieved from the rack. By default, the orders are generated randomly.

Lift

This is a vertical elevator. On this elevator a load attachment device is mounted. With this device the elevator is able to manipulate boxes. The lift has to deliver boxes from the I/O-position to the buffer and vice versa.

3.3 Function explanation

As seen above in Table 3-1, the functions are divided in four groups. Each group, with the corresponding functions, is described briefly in the following sections.

3.3.1 System configuration

All the functions within the 'system configuration' are needed to define the basic system. This means defining the configuration of the rack, kinematic parameters, cycle times and dead times.

3.3.1.1 Kinematic parameters for shuttle and lift

With this function the kinematic parameters for lift and shuttle are specified. The kinematic parameters are:

- the maximum velocity of the shuttle in x-direction
- the maximum velocity of the lift in y direction
- the acceleration and deceleration of the shuttle in x-direction
- and the acceleration and deceleration of the lift in y-direction

The kinematic parameters influence the driving behaviour of lift and shuttle (trapezoid / triangular behaviour).

3.3.1.2 Rack dimensions

With this function, the amount of columns, tiers and the rack depth is defined. Figure 3-1 shows a single deep rack, while Figure 3-2 shows a multiple deep rack, in this case the rack depth is three bays.

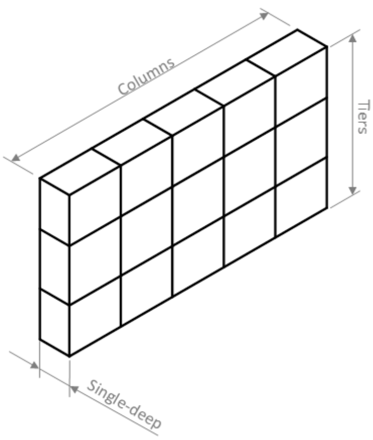

Figure 3-1: Single deep rack

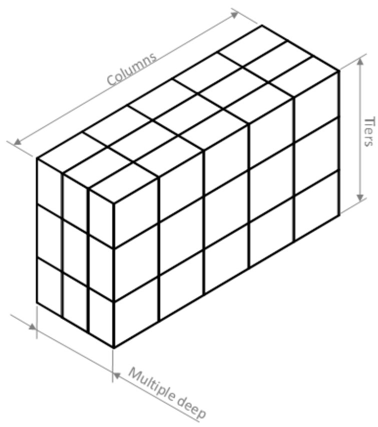

Figure 3-2: Multiple-deep rack

In Figure 3-3 the arrangement of the rack in the aisle is displayed. The rack is located on the left and right side of the aisle. On the front side of the rack there is the buffer. For each tier a buffer is available. Also the buffer capacity, i.e. how much boxes can be stored in the buffer at the same time, can be defined with a function.

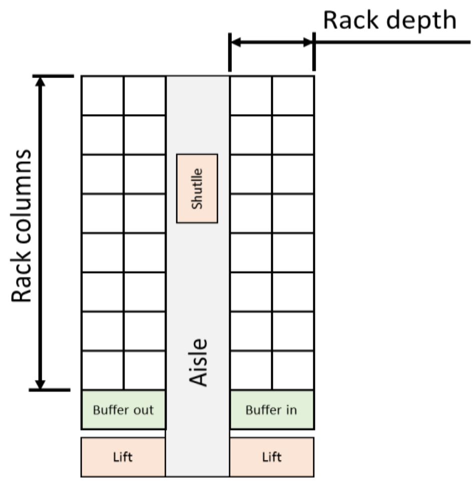

Figure 3-3: Plan view from an aisle

3.3.1.3 Bay dimensions

Depending on the goods which have to be stored in the rack, the bay width and height are specified. Bigger bays lead to a bigger rack. Figure 3-4 illustrates the bay dimensions.

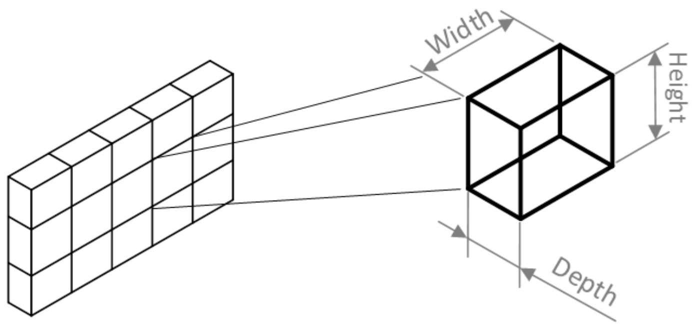

Figure 3-4: Bay dimension

3.3.1.4 Cycle times

The shuttle and lift need a certain time for the loading and unloading process of boxes. Therefore the

- cycle time for the shuttle in z-direction,
- a factor for the cycle time in z-direction for each additional rack depth,
- the lift cycle time in z-direction,
- and the time the shuttle needs to load or unload a box from the buffer has to be specified in advance.

3.3.1.5 Dead times

The dead time is a proportion of the cycle time e.g. for reaction time or switching time [ArF09]. The dead times for the shuttle and for the lift are taken into account with the function 'dead times'. These dead times occur in the simulation during the loading or unloading of boxes. Thus the dead times are needed to calculate the cycle times.

3.3.1.6 Buffer capacity

Each tier of the rack has a buffer. At the buffer the boxes are stored temporarily. The buffer is important to enable parallel working for lift and shuttle. The amount of how many boxes can be stored into the buffer per tier is determined by the buffer capacity. Figure 3-5 illustrates a rack configuration with a buffer capacity of two.

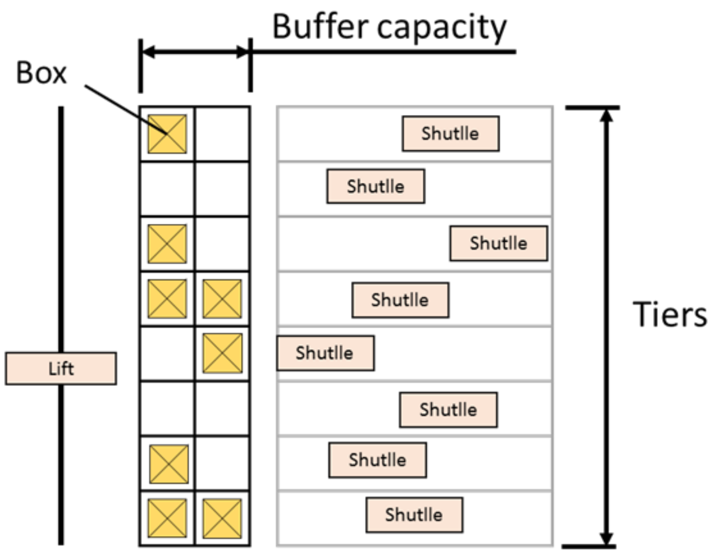

Figure 3-5: Buffer at the front side of the rack

3.3.2 Storage strategies

The functions for ‘storage strategies’ are used to define the way how boxes are handled. That includes the way how they are stored and the handling sequence. Also strategies for lift and shuttle can be defined.

3.3.2.1 Shuttle buffer position

The buffer does not have to be positioned at the front side of the rack. With the function ‘shuttle buffer position’ the buffer can be at every position on the rack. Figure 3-6 shows three possible buffer positions. First, the buffer is located at the beginning of the rack (a), second the buffer is located in the middle of the rack (b) and third the buffer is located at the end of the rack (c). The position has an effect on the average travel distance for the shuttle.

$$\text{Buffer position} = 0$$

$$\text{Buffer position} = \frac{L_{Rack}}{2}$$

$$\text{Buffer position} = L_{Rack}$$

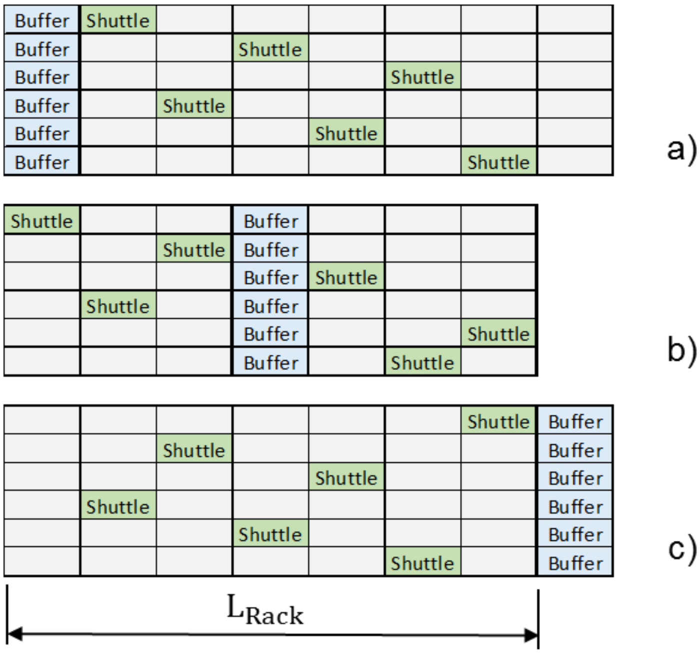

Figure 3-6: Possible buffer positions

3.3.2.2 Lift strategies

For the lift, different strategies can be set. This implies the number of load attachment devices and the number of lifts per aisles. If the there are two lifts per aisle, an additional optional function is available.

Load carrier capacity

A load attachment device (LAD) is mounted on the lift. This LAD allows the lift to load boxes and transport them. The capacity of how many boxes the lift can carry at once is defined with the 'load carrier capacity' function.
Figure 3-7 a) shows exemplary a load attachment device with a capacity of one while Figure 3-7 b) shows a capacity of two.

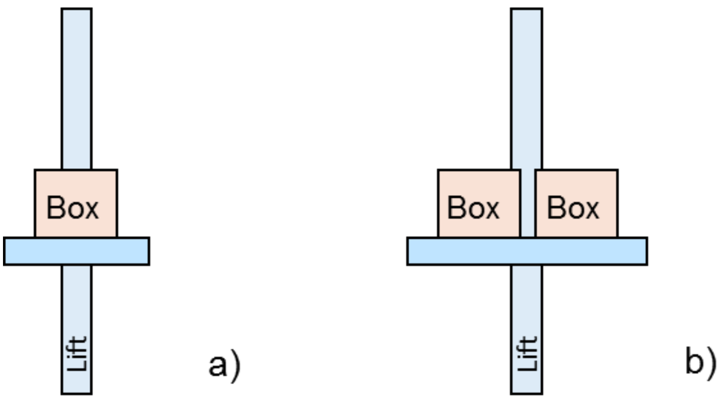

Figure 3-7: Different capacities for lift load attachment device

Number of lifts per aisle

With this function it can be chosen if there is one or two lifts per aisle. With two lifts per aisle an additional function is possible.

Lift strategies for two lifts per aisle

When the aisle has only one lift, this lift has to carry out the storage and retrieval of boxes. But with two lifts per aisle it is possible that one lift is in charge for storage of boxes and the other one is in charge for retrieval of boxes.

3.3.2.3 Lift input position

With this function the location of the input position for the lift is determined. The input position can be at every position of the rack. The position influences the average travel distance of the lift. Figure 3-8 illustrates three possible lift input positions. First, the input position is at the bottom of the rack (a), second it is located in the middle of the rack height (b) and third the input position is at the very top end of the rack height (c).

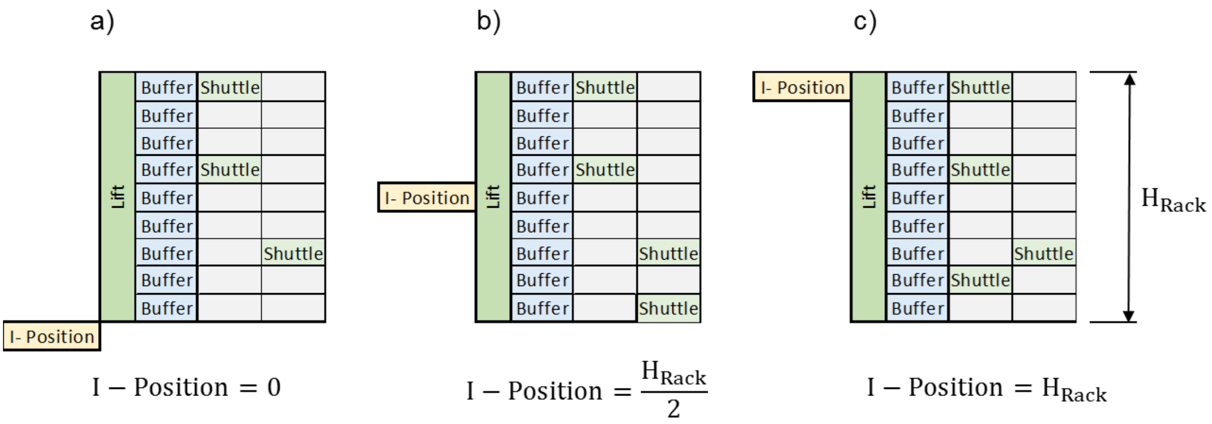

Figure 3-8: Possible lift input positions

3.3.2.4 Lift output position

By the ‘lift output position’ function the position of the output can be configured. The difference to the ‘lift input position’ function is that up to five output positions at the same time can be located at the rack. Figure 3-9 shows a possible configuration. In this case, the rack consists of nine tiers and has three output positions. The first is in the first tier, the second in the 5th tier and the third output position is in the 9th tier.

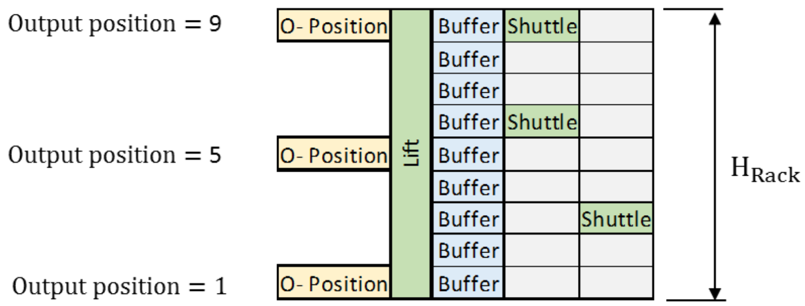

Figure 3-9: Possible output position configuration

3.3.2.5 Storage sequence

With the function 'storage sequence', the course of handling the boxes is defined. There are three possible strategies to handle boxes within the system. First, during the simulation boxes are only retrieved from the rack (Figure 3-10). The flow of box goes from the rack to the output position.

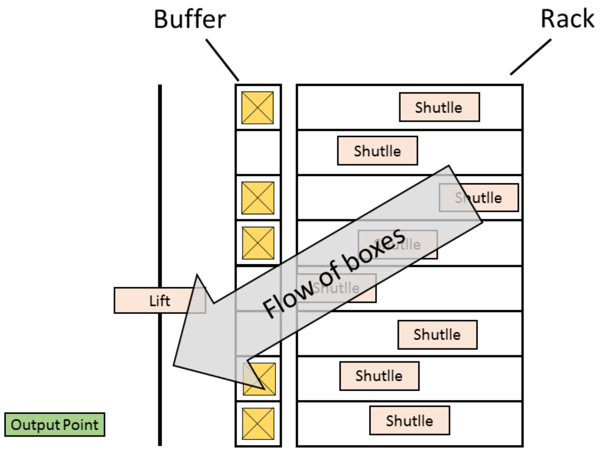

Figure 3-10: Flow of boxes during retrieval process

Second, the boxes are only stored into the rack (Figure 3-11). The flow of boxes goes from the input position into the rack.

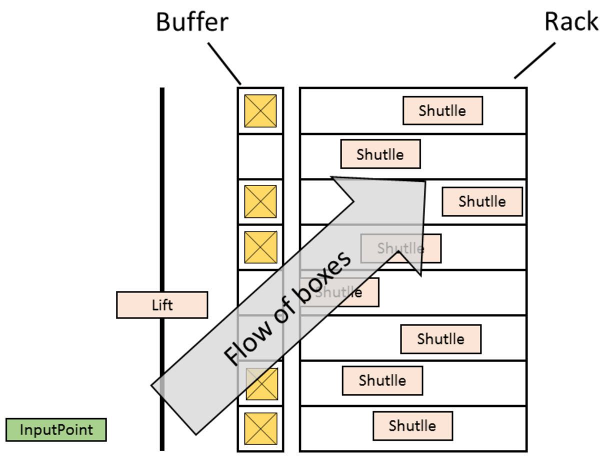

Figure 3-11: Flow of boxes during storage process

The third strategy is a combination of storage and retrieval operations (Figure 3-12). In this case the flow of boxes goes from the rack to the output position and form the input position into the rack.

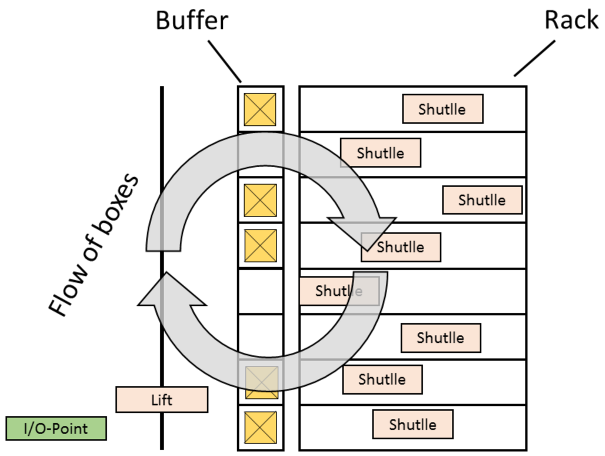

Figure 3-12: Flow of boxes during storage and retrieval process

3.3.2.6 Rack occupancy strategies

The ‘rack occupancy strategies’ function enables four different strategies to occupy the rack.

- Random rack occupancy
- Rack occupancy from behind
- Occupy with occupancy list
- Occupy through storage process

Random rack occupancy

With this strategy the rack is occupied randomly by boxes. The boxes are distributed evenly on the rack. The number of how many boxes shall be in the rack is specified by the rack occupancy rate.

Rack occupancy from behind

This strategy is the same as the ‘random rack occupancy’ strategy. The only difference is if the rack is multiple deep, the bays in the depth are occupied at first. It has the effect, that there are no empty bays between occupied bays. Figure 3-13 illustrates exemplary the rack occupancy for a multiple deep rack with the ‘random rack occupancy’ strategy. It can be seen that there are some empty bays between occupied bays.

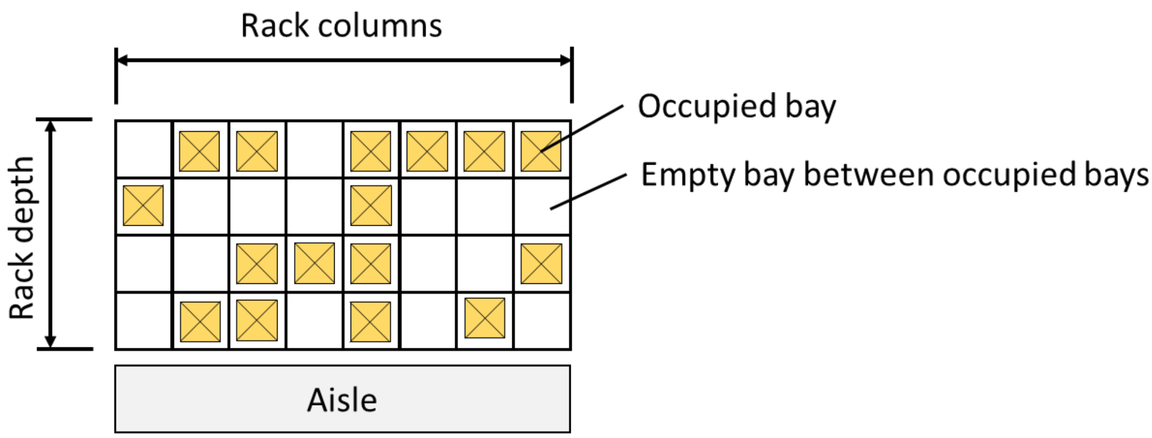

Figure 3-13: Random rack occupancy

In Figure 3-14 a multiple deep rack is displayed. In this case the rack is occupied with the 'rack occupancy from behind' mode. The deeper layers of the rack are occupied at first thus no empty bays between occupied bays occur.

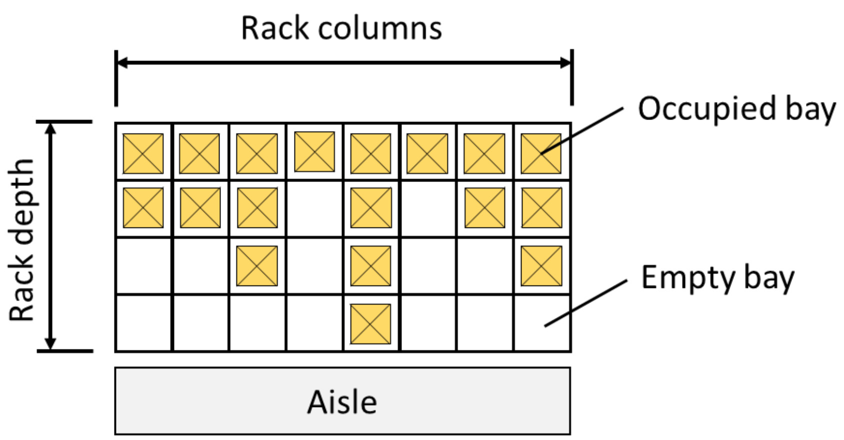

Figure 3-14: Rack occupancy from behind

Occupy with occupancy list

With this strategy the rack is occupied according to an occupancy list. In this list the exact location of every box is listed.

Occupy through storage process

In this strategy the rack is by default empty. During the simulation the boxes are stored into the rack and thus the rack will be filled. When the simulation is finished the rack is randomly occupied with boxes.

3.3.2.7 Parameter variation

With the function 'parameter variation' specific parameters can be varied during a simulation run. Thus characteristic curves from the output data can be gained.

3.3.2.8 ABC- distribution

With the 'ABC- distribution' function the system distinguishes between three classes of goods (A-, B- and C- goods). Therefor the proportions of the three different goods on the overall orders have to be considered. Furthermore sections in the rack are reserved for each kind of group. Thus the rack is grouped in three sections (A-, B- and C-section). Also the way how these sections are created can be specified. Either the sections are arranged as blocks (Figure 3-15), as columns (Figure 3-16) or as rows (Figure 3-17).

	Columns	1	2	......	45	46	......	70	71	72	......	99	100
	10	C	C	...	C	C	...	C	C	C	...	C	C
	9	C	C		C	C		C	C	C		C	C
	8	C	C		C	C		C	C	C		C	C
	7	B	B		B	B		B	B	C		C	C
Tiers	6	B	B		B	B		B	B	C		C	C
	5	B	B		B	B		B	B	C		C	C
	4	A	A		A	B		B	B	C		C	C
	3	A	A		A	B		B	B	C		C	C
	2	A	A		A	B		B	B	C		C	C
	1	A	A	...	A	B	...	B	B	C	...	C	C

Figure 3-15: ABC-distribution: Block

	Columns	1	......	20	21	......	49	50	51	52	......	99	100
	10	A	...	A	B	...	B	B	C	C	...	C	C
	9	A		A	B		B	B	C	C		C	C
	8	A		A	B		B	B	C	C		C	C
	7	A		A	B		B	B	C	C		C	C
Tiers	6	A		A	B		B	B	C	C		C	C
	5	A		A	B		B	B	C	C		C	C
	4	A		A	B		B	B	C	C		C	C
	3	A		A	B		B	B	C	C		C	C
	2	A		A	B		B	B	C	C		C	C
	1	A	...	A	B	...	B	B	C	C	...	C	C

Figure 3-16: ABC-distribution: Columns

	Columns	1	2	3	......	96	97	98	99	100
	10	C	C	C	...	C	C	C	C	C
	9	C	C	C		C	C	C	C	C
	8	C	C	C		C	C	C	C	C
	7	C	C	C		C	C	C	C	C
Tiers	6	C	C	C		C	C	C	C	C
	5	B	B	B		B	B	B	B	B
	4	B	B	B		B	B	B	B	B
	3	B	B	B		B	B	B	B	B
	2	A	A	A		A	A	A	A	A
	1	A	A	A	...	A	A	A	A	A

Figure 3-17: ABC-distribution: Rows

3.3.2.9 Order list

With this functions the orders are fulfilled according to an order list instead of generated randomly. The order list has to be created in advance.

3.3.2.10 Order sequencing

With this function the order can be handled batch-wise. The batch is generated randomly but the number of boxes within a batch is predefined. There are three possibilities to define the batch size:

- Constant number of boxes within a batch
- Define the batch size with a lower and upper limit
- Normal distributed batch size. In this case, the size is defined by the mean value and the standard deviation

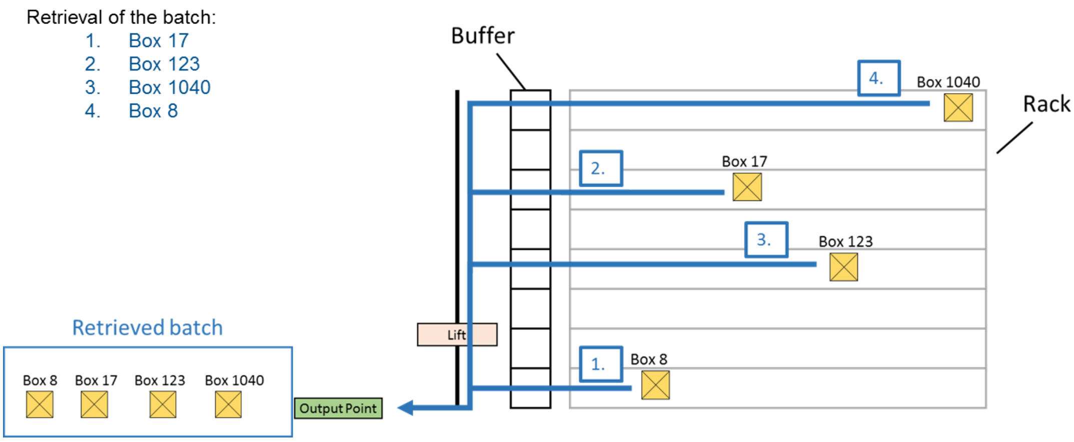

Figure 3-18: Batch-wise order execution

3.3.2.11 'Real' Random numbers

With this function, the seed value for the VBA random number generator can be varied. Either the default seed value is used or the actual time is set as seed value. To set the actual time as seed value, the VBA Timer function is used. This function returns a number with the data type Single, representing the number of seconds elapsed since midnight [MC16b].

3.3.3 Performance data

The functions for the 'performance data' group are used to gain information about a simulation run. That includes system throughput, utilizations and the sequence of events. Furthermore, it is possible to evaluate the tool itself, in order to come to a more transparent tool.

3.3.3.1 Throughput calculation

This function calculates the system throughput. The throughput is the number of boxes which are stored or retrieved per hour. In Equation 3-1 n is the number of boxes which are stored or retrieved and t_t is the total time.

$$\lambda_S = \left(\frac{n}{t_t}\right) * 3600 \qquad \left[\frac{\#}{h}\right]$$

Equation 3-1: System throughput

3.3.3.2 Lift utilization

The function to calculate the lift utilization is the ratio between the lift waiting time and the total time (Equation 3-2). The utilization can only have values between 0 and 1. The average utilization is the sum of the single lift utilization divided by the number of lifts.

$$\rho_L = 1 - \left(\frac{t_w}{t_t}\right)$$

Equation 3-2: Lift utilization

3.3.3.3 Shuttle utilization

The shuttle utilization is the ratio between the shuttle waiting time and the total time (Equation 3-3). The utilization can only have values between 0 and 1. The average utilization is the sum of the single shuttle utilizations divided by the number of shuttles.

$$\rho_S = 1 - \left(\frac{t_w}{t_t}\right)$$

Equation 3-3: Shuttle utilization

3.3.3.4 Tracking of specific box

With this function a specific box is tracked during the simulation. All the events concerning this box are then listed. Up to five different boxes can be tracked simultaneously.

3.3.3.5 Display occupied rack

The occupancy of the rack is displayed. Each single box with the exact location within the rack is listed. Thus the rack occupancy can be evaluated.

3.3.3.6 Display fulfilled order list

To ensure that the order list is carried out correctly, the orders which are fulfilled during the simulation can be displayed.

3.3.3.7 Display fulfilled random orders

All the single orders during a simulation can be stored and detail information of the orders can be displayed.

3.3.3.8 Display ABC- distribution

The ABC rack occupancy and the order proportion of the ABC-goods are displayed. This function serves to evaluate the ABC- distribution.

3.3.3.9 Display event list

All the single actions which are happening during the simulation can be displayed. These actions are sorted in ascending order. For each event, detailed information is provided.

3.3.3.10 Display batch size

If the storage strategy 'order sequencing' is chosen, each single batch can be displayed. Each batch consists of a certain number of boxes, each of these boxes are then displayed and assigned to the corresponding batch.

3.3.3.11 Additional statistics

Additional information about the simulation run is displayed. Thus further information about the system is gained. The additional statistics run as follows:

- Mean cycle time
- Mean relocation time
- Mean waiting time
- Mean waiting time in buffer
- Mean waiting time for free buffer
- Amount retrieved boxes
- Amount stored boxes
- Mean relocation cycles
- Buffer utilization

3.3.3.12 Examine convergence

An important criterion for a simulation model is that the model needs to converge. That means the model delivers always the same results for a simulation run with the same parameters. With this function it is examined whether the simulation is convergence or not.
The convergence truncation criterion is displayed in Equation 3-4. For this equation it is assumed that the distribution is unknown, the expected value μ is unknown and the variance σ^2 is unknown. The value 1,96 is the $(1-\frac{\alpha}{2})$- Quantil for a significance level of 95%. [JGL10] The maximum permitted value for the confidence amplitude is 1 second.

$$1{,}96 * \sqrt{\frac{\frac{1}{n-1}\sum_{i=1}^{n}(t_{cycle} - \frac{1}{n}\sum_{i=1}^{n} t_{cycle_i})^2}{n}} \leq 1s$$

Equation 3-4: Convergence truncation criterion [JGL10]

3.3.3.13 Display random numbers

The simulation is using the internal Excel VBA random number function -Rnd(). This function is generating uniformly distributed random numbers. In order to examine the random number function, the function can be tested and the created random numbers can be displayed.

3.3.3.14 Quality of rack occupancy

For each simulation run, the rack is occupied with boxes. This occupancy is uniformly distributed and it also uses the internal Excel VBA random number function – Rnd(). With the function ‘quality of rack occupancy’, the quality of the rack occupancy can be examined.

3.3.3.15 Quality of order creation

The orders during the simulation are created randomly. Therefore the Excel VBA random number function is used. The quality of the order creation can be examined with the function ‘quality of order creation’.

3.3.4 Internal calculation functions

These functions are used for internal calculations only. The tool is executing these functions during a simulation run.

3.3.4.1 Calculate distance

Calculate the driving distance for shuttle and lift. The distance is the difference between target position and current position. The variable D in Equation 3-5 is the column width or tier height in millimetres. $P_{current}$ is the actual column of the shuttle or the actual tier of the lift. P_{target} is the target column of the shuttle or the target tier of the lift.

$$s = \left(P_{target} - P_{current}\right) * \left(\frac{D}{1000}\right) \qquad [\,m\,]$$

Equation 3-5: Calculate distance

3.3.4.2 Calculate travel time

The travel time defines the time for shuttle or lift to move from current position to target position. When the distance is long enough to accelerate to maximum velocity the travel time is calculated with Equation 2-4 (Trapezoid behaviour). If the distance between the current position and the target position is not long enough to accelerate to maximum velocity, the travel time is calculated with Equation 2-2 (Triangular behaviour).

3.3.4.3 Loading time shuttle

This function calculates the time for the shuttle to store or to retrieve a box from the rack. For a multiple deep rack the storage and retrieval time is longer in comparison to a single deep rack. Equation 3-6 illustrates the way to calculate the loading time for a single-deep rack. Equation 3-7 shows how to calculate a multiple deep rack. In this case each additional depth, compared to the single deep rack, has to be taken into account.

Single-deep rack: $$t_{SR} = 2 * t_z + t_0 \qquad [s]$$

Equation 3-6: Loading time single deep rack

Multiple-deep rack: $$t_{SR} = 2 * t_z + i * t_{zd} + t_0 \qquad [s]$$

Equation 3-7: Loading time multiple deep rack

t_{SR}...Time to store or retrieve a box [s]
t_z...Shuttle cycle time in z-direction [s]
t_0...Dead time proportion [s]
t_{zd}...Cycle time in z-direction for multiple-deep rack [s]
i...additional rack depth

3.3.4.4 Loading time lift

With this function the loading time for the lift is calculated. This implies the time for the lift to store or retrieve a box from the buffer and the time to receive a box from the input position or to handover a box to the output position. With the loading time is calculated. The equation composes of the lift cycle time in z-direction (t_z) and the dead time proportion (t_0).

$$t_{SR} = 2 * t_z + t_0 \qquad [s]$$

Equation 3-8: Loading time lift

3.3.4.5 Shuttle find empty bay

When the shuttle is storing a box into the rack, it will search for an empty bay. The shuttle choses the closest empty bay. Figure 3-19 illustrates that the shuttle has more than one possibility to store the box. The shuttle selects the closest bay and stores the box into it (Figure 3-20).

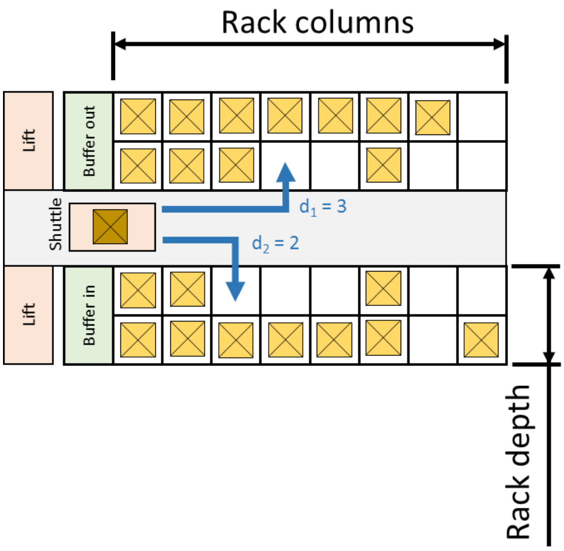

Figure 3-19: Find empty bay

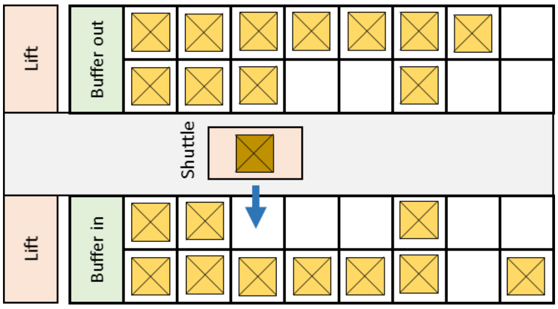

Figure 3-20: Closest bay is found

3.3.4.6 Relocation of a box

When the shuttle has to retrieve a box, but this target box is obstructed, the shuttle has to relocate the obstructing box. Relocating needs time and hence increases the cycle time for retrieving procedures Figure 3-21 illustrates a possible scenario how a box can be obstructed by another one.

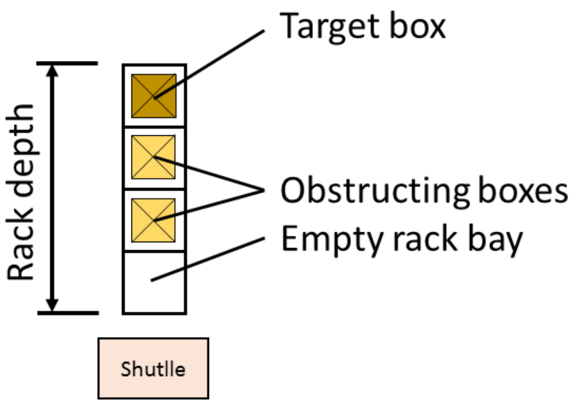

Figure 3-21: Obstructed box

When the target box is obstructed, the shuttle has to relocate the obstructing box and find an empty bay for this box (Figure 3-22).

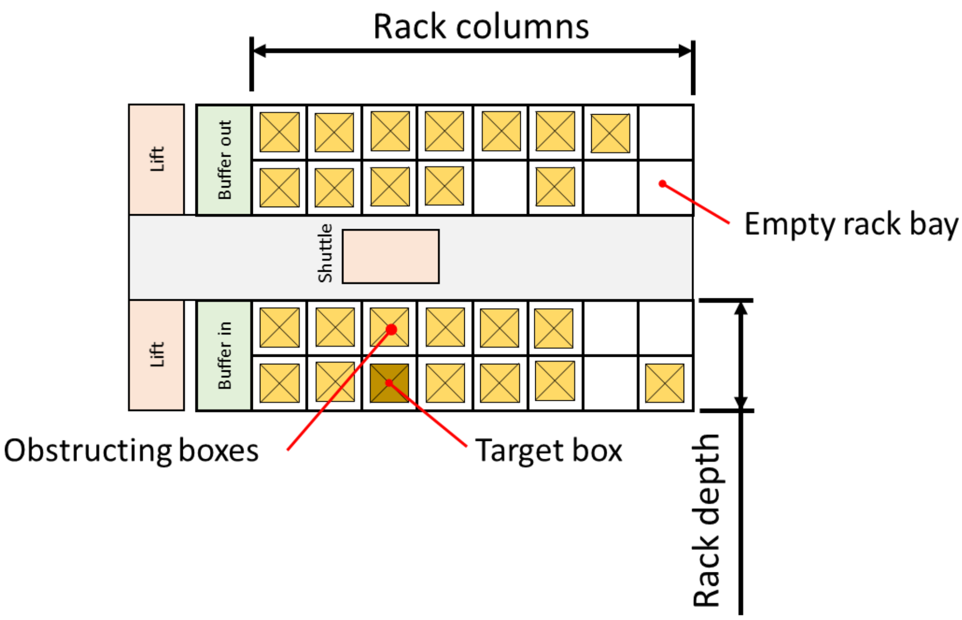

Figure 3-22: Possible scenario of an obstructed box

When an empty bay is found, the obstructing box can be relocated (Figure 3-23). The shuttle will always choose the nearest empty bay.

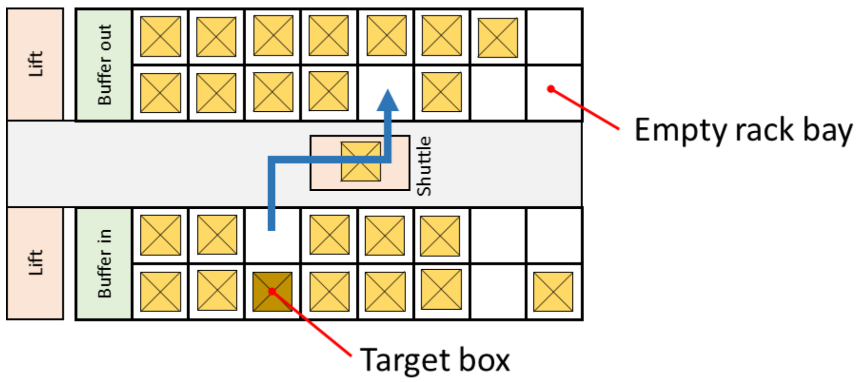

Figure 3-23: Relocation of the obstructing box

After the relocation of the obstructing box, the shuttle can retrieve the target box (Figure 3-24). It can also happen that the target box is obstructed by more than one box. The shuttle has to relocate all these obstructing boxes. These processes are then executed as described above.

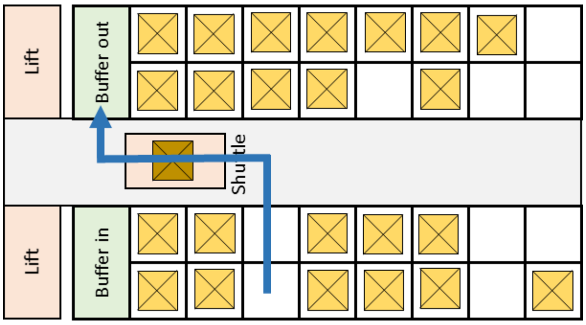

Figure 3-24: Retrieval of the target box.

4 Methodology

In this chapter the development of the tool ‘Shuttle analysis’ is described. The problem analysis of chapter 2 results into the tool specification of chapter 3. These specifications for the tool functionality are now implemented. After the implementation the tool is verified.
In order to develop the tool a simulation study was carried out. The theoretical background of a simulation study is discussed in chapter 2.4.

4.1 Data acquisition

A lot of data regarding the rack dimensions and kinematic parameters for the lift and shuttle are provided by the Institute of Logistics Engineering. Data for storage strategies are found in the literature e.g. ABC-distribution. Performance data like system throughput from other shuttle systems is hard to find. This has two main reasons. First, other studies have investigated in a shuttle system with more than one aisle (e.g. [MMP12+]) and second it is hard to get real performance data from the manufacturing companies.

4.2 Model design

After defining the objectives and the data acquisition, the conceptual model was designed. Figure 4-1 illustrates the entity relationship model (ERM) of the conceptual model. The model consists of five main parts: The lift, the order, the shuttle, the rack and the buffer. Each part has different input parameters, output parameters and attributes. The rack can have more than one lift and has in each tier a shuttle. Also in each tier a buffer is located. The orders are assigned to the shuttles and to the lifts. All together they are representing the complete shuttle system.
The order management for the lift is shown in Figure 4-2. It shows a flow chart which contains the process sequence of the lift logic. The shuttle logic is displayed in Figure 4-3. In this flow chart the process sequence to handle the orders is illustrated.

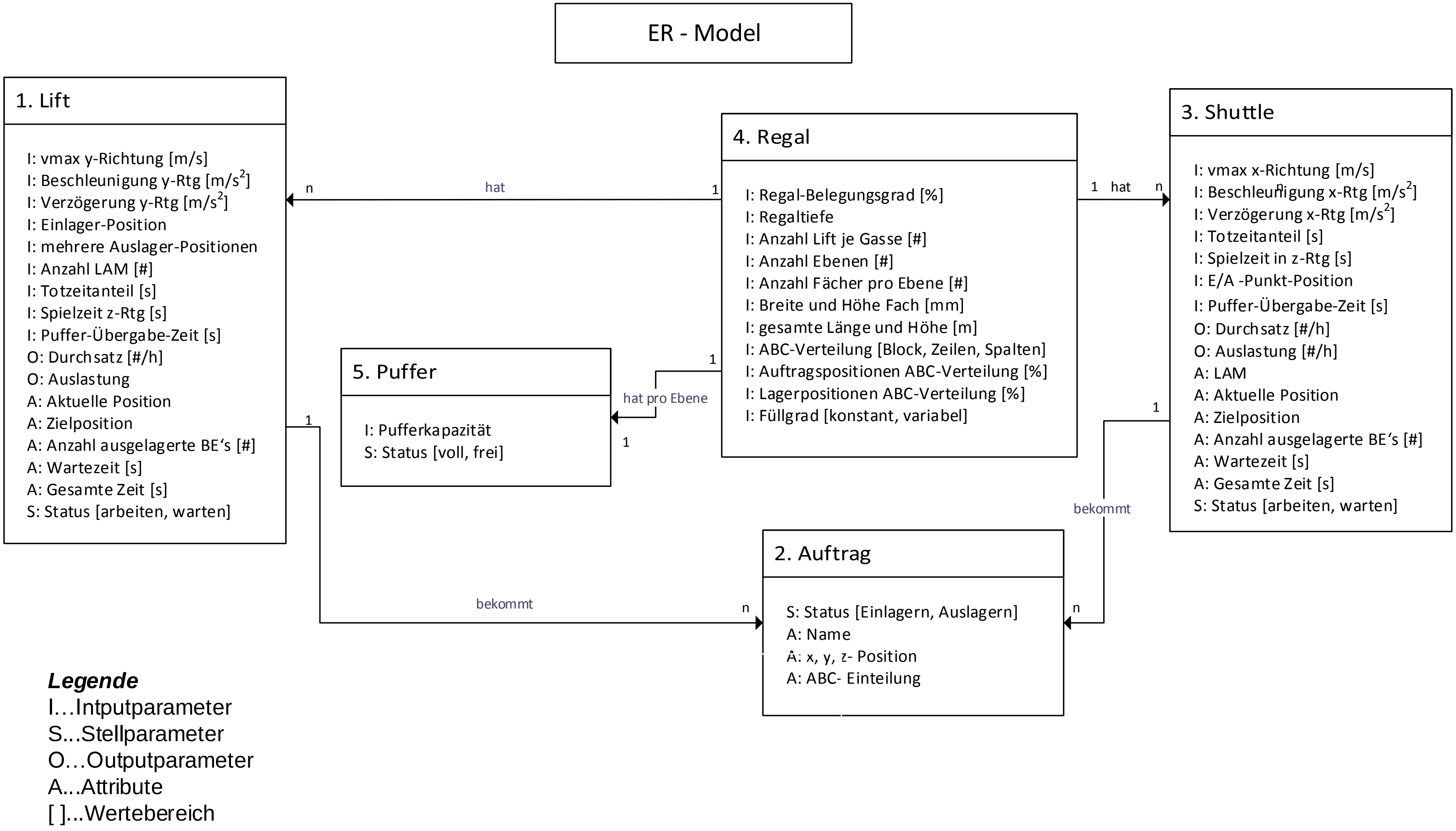

Figure 4-1: ERM of the conceptual model

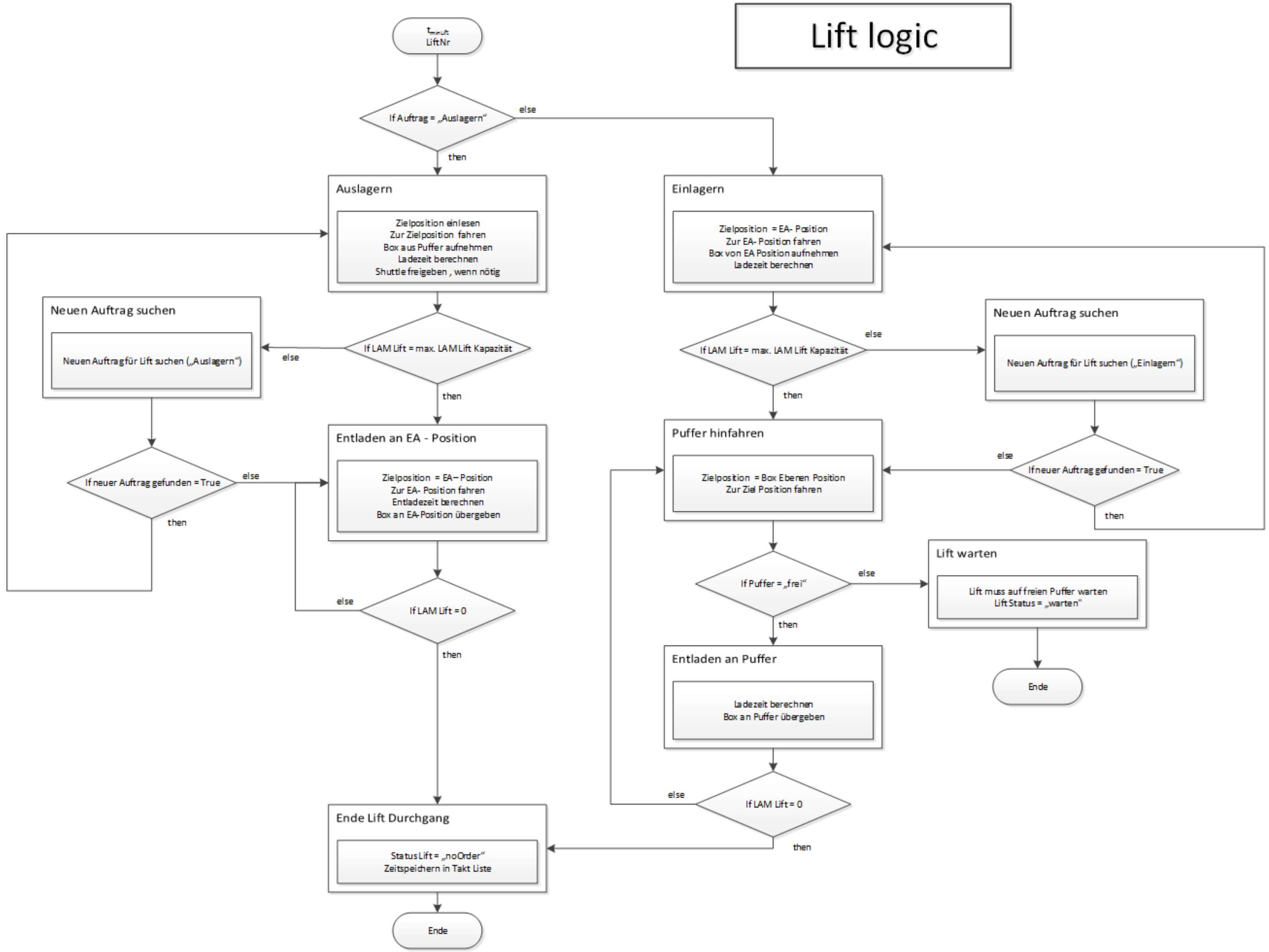

Figure 4-2: Lift logic

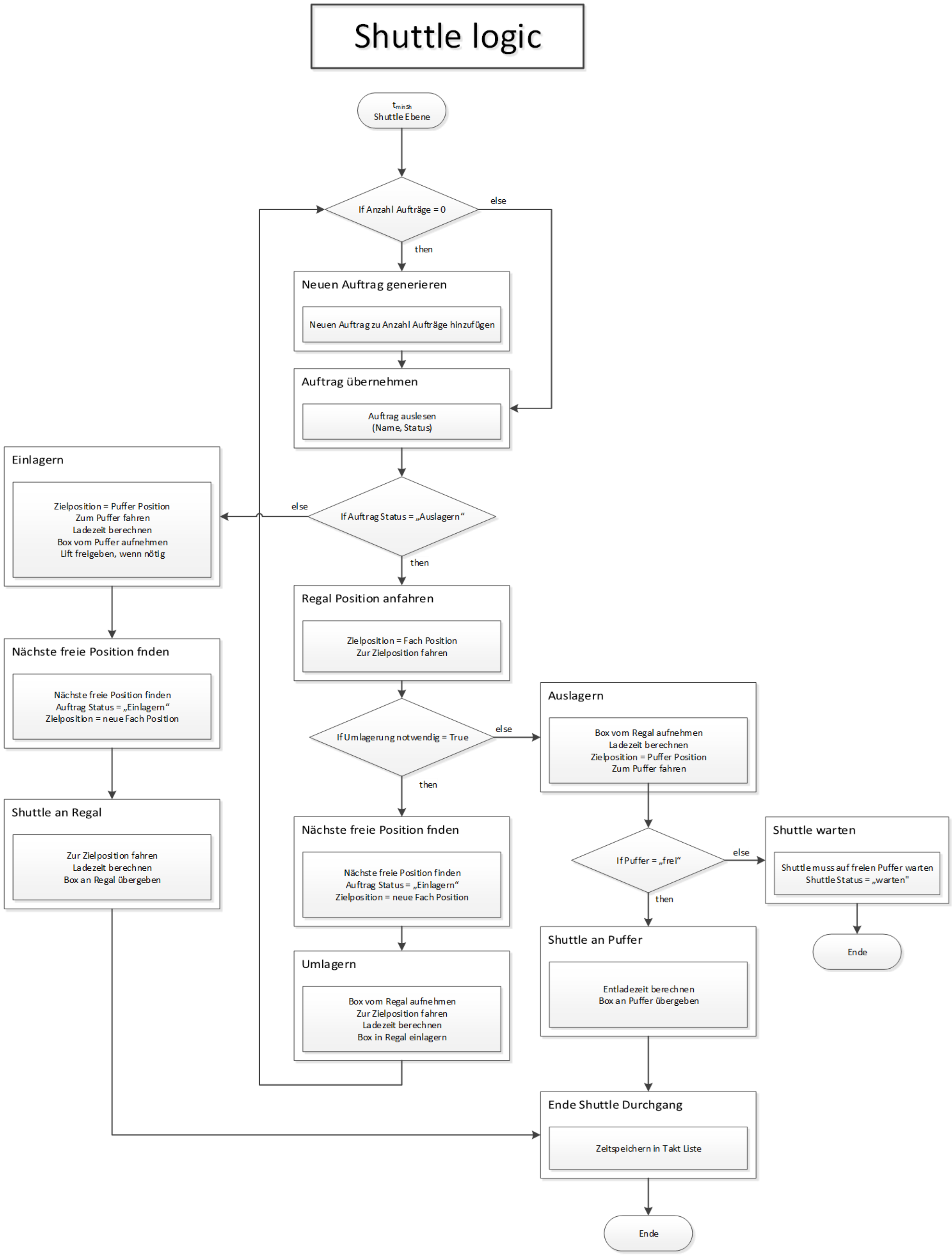

Figure 4-3: Shuttle logic

4.3 Model implementation

The shuttle logic and the lift logic with all the functions mentioned in chapter 3.3 are implemented in a model framework. In this framework the variables are declared, the input data prepared and other calculations are carried out. The whole conceptual model is created within Visual Basic for Applications.

4.4 Model verification

After the implementation, the software model is has to be verified. The syntax of the code is checked by the VBA software itself. Thus the code is syntactical correct. The functionality of the software model is verified with the methods mentioned in chapter 2.4.5. The verification process is important to confirm the correct execution of the functions.

In the following section some of the verified functions or functions combinations are described.

4.4.1 Retrieval process

The boxes are only retrieved from the rack. The deviation between analytic throughput and throughput from the simulation is examined. The number of tiers and the number of columns have an influence on the throughput. The first step is to examine the shuttle and lift separately and then the combination of both to examine the system throughput. The verification method is the sub model testing. Table 4-1 illustrates the compartment dimensions and the kinematic parameters for lift and shuttle. This input data is used for all the investigations in the retrieval process.

Compartment	
Height:	350 [mm]
Width:	550 [mm]
Shuttle	
Acceleration:	1 [m/s^2]
Deacceleration:	1 [m/s^2]
Velocity:	2,5 [m/s]
Cycle time z-dir.:	3,5 [s]
Dead time:	1 [s]
Puffer transition time:	1,5 [s]
Lift	
Acceleration:	1 [m/s^2]
Deacceleration:	1 [m/s^2]
Velocity:	1 [m/s]
Cycle time z-dir.:	1,5 [s]
Dead time:	0,5 [s]

Table 4-1: Input data for retrieval process

Table 4-2 shows the outcome of the shuttle retrieval process. Here the shuttle is examined, how throughput depends on the number of rack columns. The simulation throughput is compared with the analytic throughput. The analytic throughput is calculated by one divided by the average cycle time. The average cycle time in turn is calculated by the average distance to the buffer. This is half of the rack length. With the given acceleration, deceleration and velocity of the shuttle, it is checked if the movement behaviour, to overcome the average distance to the buffer, is triangular or trapezoid. Then the average cycle time is calculated. The calculation for a triangular movement is shown in Equation 2-2 and for a trapezoid movement in Equation 2-4. A detailed display of the throughput calculation is given in chapter 4.4.2.
In this case the deviation between the analytic and the simulation throughput is little. The deviation describes the difference from the actual value (simulation throughput) to the target value (analytic throughput).
The characteristic curve for the shuttle throughput is shown in Figure 4-4. With an increasing transportation route (more columns) the system throughput decreases. Due to the small deviation between the analytic and simulation throughput and the characteristic curve, it can be said that the shuttle retrieval process in the tool is processing correct.

		Analytic throughput shuttle		Simulation throughput shuttle Outcome Monte-Carlo-Simulation			
	Number rack columns	max. Throughput		max. Throughput		Deviation	
Shuttle retrieval	100	98,63	[#/h]	98,27	[#/h]	0,37	[%]
	150	75,79	[#/h]	75,59	[#/h]	0,27	[%]
	200	61,54	[#/h]	61,33	[#/h]	0,34	[%]
	250	51,80	[#/h]	51,65	[#/h]	0,29	[%]
	300	44,72	[#/h]	44,64	[#/h]	0,19	[%]
	350	39,34	[#/h]	39,26	[#/h]	0,22	[%]
	400	35,12	[#/h]	35,04	[#/h]	0,23	[%]
	450	31,72	[#/h]	31,66	[#/h]	0,17	[%]
	500	28,92	[#/h]	28,89	[#/h]	0,08	[%]
	550	26,57	[#/h]	26,53	[#/h]	0,16	[%]
	600	24,57	[#/h]	24,52	[#/h]	0,22	[%]
	650	22,86	[#/h]	22,80	[#/h]	0,24	[%]
	700	21,36	[#/h]	21,33	[#/h]	0,17	[%]

Table 4-2: Outcome of shuttle retrieval process

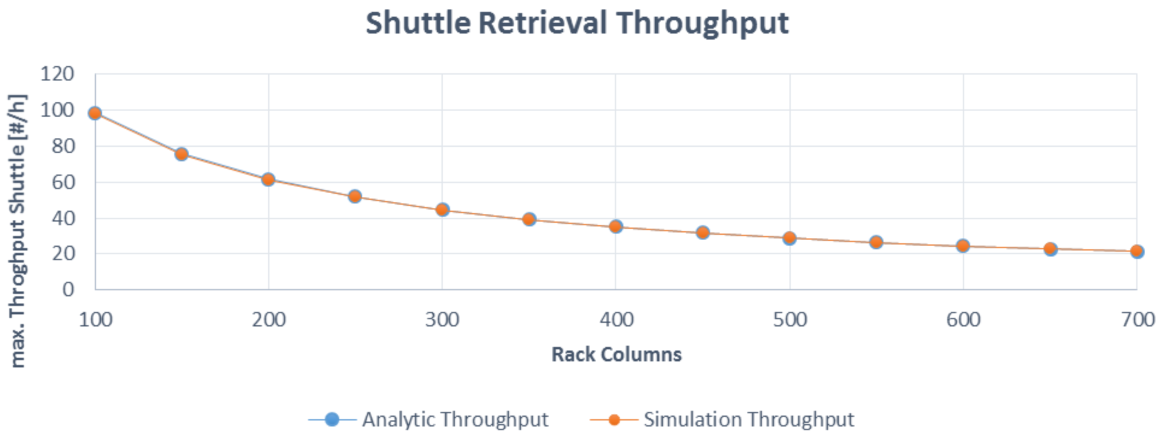

Figure 4-4: Shuttle throughput characteristic curve

The outcome of the lift retrieval process is shown in Table 4-3. This table highlights the analytic throughput versus the simulation throughput depending on the number of tiers. The analytic throughput for the lift is calculated in the same way as for the shuttle. But in this case the average distance to buffer is calculated with the rack height.
The characteristic curve of the lift throughput is illustrated in Figure 4-5. With increasing length of the transportation route (number of tiers) the lift throughput decreases. There is only a small deviation between the analytic and simulation throughput. Also the characteristic curve is consistent. Thus the lift retrieval process within the tool is processing correct.

		Analytic throughput lift		Simulation throughput lift			
				Outcome Monte-Carlo-Simulation			
	Number rack tiers	max. Throughput		max. Throughput		Deviation	
Lift retrieval	5	326,60	[#/h]	326,59	[#/h]	0,00	[%]
	10	281,00	[#/h]	280,98	[#/h]	0,01	[%]
	15	247,01	[#/h]	247,01	[#/h]	0,00	[%]
	20	220,44	[#/h]	220,44	[#/h]	0,00	[%]
	25	199,07	[#/h]	199,06	[#/h]	0,00	[%]
	30	181,48	[#/h]	181,48	[#/h]	0,00	[%]
	35	166,75	[#/h]	166,76	[#/h]	0,01	[%]
	40	154,24	[#/h]	154,24	[#/h]	0,00	[%]
	45	143,48	[#/h]	143,50	[#/h]	0,02	[%]
	50	134,12	[#/h]	134,12	[#/h]	0,00	[%]

Table 4-3: Outcome of lift retrieval process

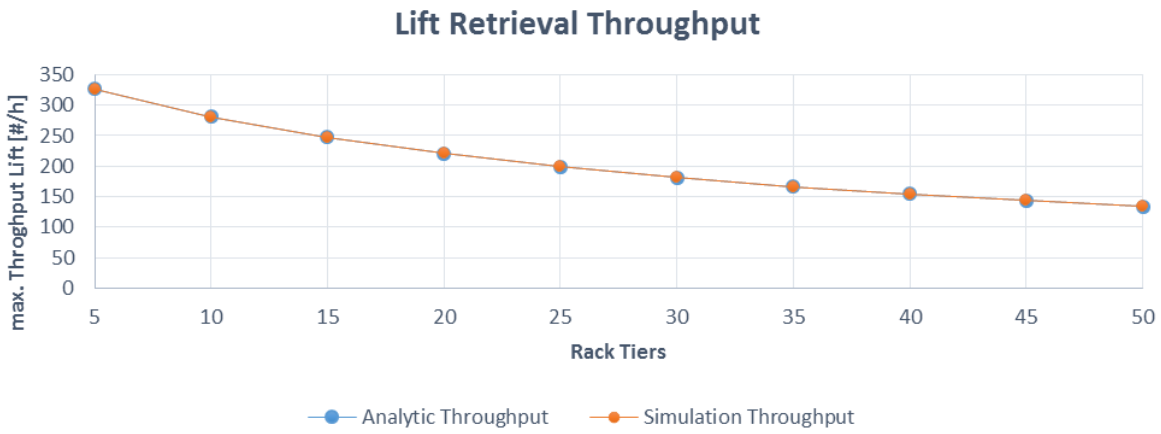

Figure 4-5: Lift throughput characteristic curve

In the following the shuttle retrieval process and the lift retrieval process are combined to examine the system retrieval throughput. Table 4-4 illustrates the comparison of the analytic system throughput and the system simulation throughput. In this case the number of tiers is constant with ten and the number of columns is variable. The characteristic curve for this setting is illustrated in Figure 4-6. Until the rack has 500 columns the lift is the limiting factor. After 500 columns the shuttle is limiting the system throughout.

			Analytic system throughput		System simulation throughput Outcome Monte-Carlo-Simulation			
	NUmber rack columns	Amount rack tiers	max. System throughput		max. Throughput		Deviation	
System retrieval (constant tiers)	100	10	281,00	[#/h]	280,97	[#/h]	0,01	[%]
	150	10	281,00	[#/h]	280,96	[#/h]	0,02	[%]
	200	10	281,00	[#/h]	280,95	[#/h]	0,02	[%]
	250	10	281,00	[#/h]	280,92	[#/h]	0,03	[%]
	300	10	281,00	[#/h]	280,95	[#/h]	0,02	[%]
	350	10	281,00	[#/h]	280,90	[#/h]	0,04	[%]
	400	10	281,00	[#/h]	280,87	[#/h]	0,05	[%]
	450	10	281,00	[#/h]	280,69	[#/h]	0,11	[%]
	500	10	281,00	[#/h]	280,47	[#/h]	0,19	[%]
	550	10	265,68	[#/h]	264,75	[#/h]	0,35	[%]
	600	10	245,73	[#/h]	245,29	[#/h]	0,18	[%]
	650	10	228,57	[#/h]	227,83	[#/h]	0,33	[%]
	700	10	213,65	[#/h]	213,34	[#/h]	0,15	[%]

Table 4-4: Outcome of the system throughput for constant number of tiers

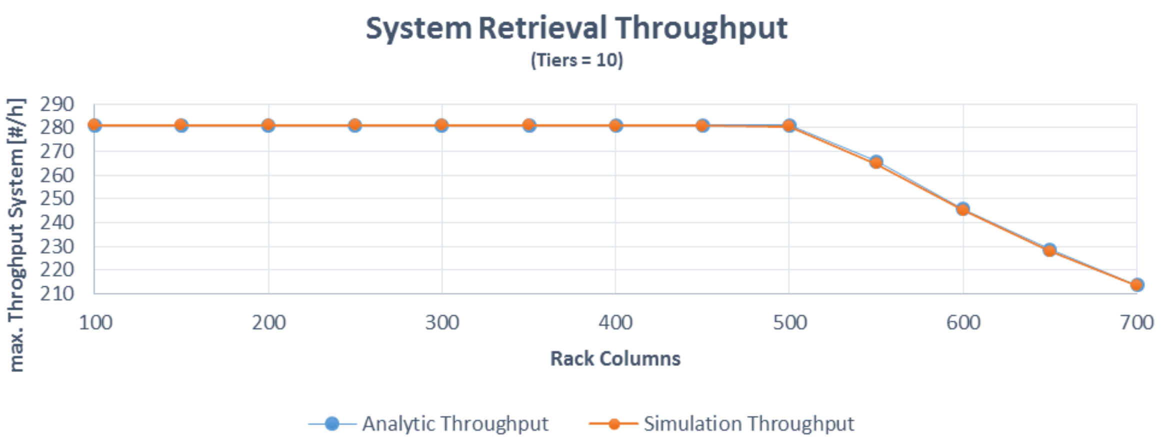

Figure 4-6: System throughput characteristic curve for constant number of tiers

Also the system retrieval throughput with constant columns (300) and variable tiers is examined. The comparison of the analytic system throughput and the simulation throughput is shown in Table 4-5. The characteristic curve for the system retrieval throughput is illustrated in Figure 4-7. Until the rack has ten tiers, the shuttle is the bottleneck of the system. After ten tiers the lift becomes the limiting factor for the system throughput.
The two characteristic curves for the system throughput are consistent and the deviation between analytic and simulation throughput is very small in both cases. Thus the tool is processing the system retrieval processes correct.

			Analytic system throughput		System simulation throughput			
					Outcome Monte-Carlo-Simulation			
	Number rack tiers	Amount rack columns	max. System throughput		max. Throughput		Deviation	
System retreival (constant columns)	5	300	223,60	[#/h]	222,57	[#/h]	0,47	[%]
	10	300	281,00	[#/h]	280,90	[#/h]	0,04	[%]
	15	300	247,01	[#/h]	246,97	[#/h]	0,02	[%]
	20	300	220,44	[#/h]	220,38	[#/h]	0,03	[%]
	25	300	199,07	[#/h]	199,01	[#/h]	0,03	[%]
	30	300	181,48	[#/h]	181,45	[#/h]	0,01	[%]
	35	300	166,75	[#/h]	166,74	[#/h]	0,01	[%]
	40	300	154,24	[#/h]	154,21	[#/h]	0,02	[%]
	45	300	143,48	[#/h]	143,47	[#/h]	0,00	[%]
	50	300	134,12	[#/h]	134,11	[#/h]	0,01	[%]

Table 4-5: Outcome of the system throughput for constant number of columns

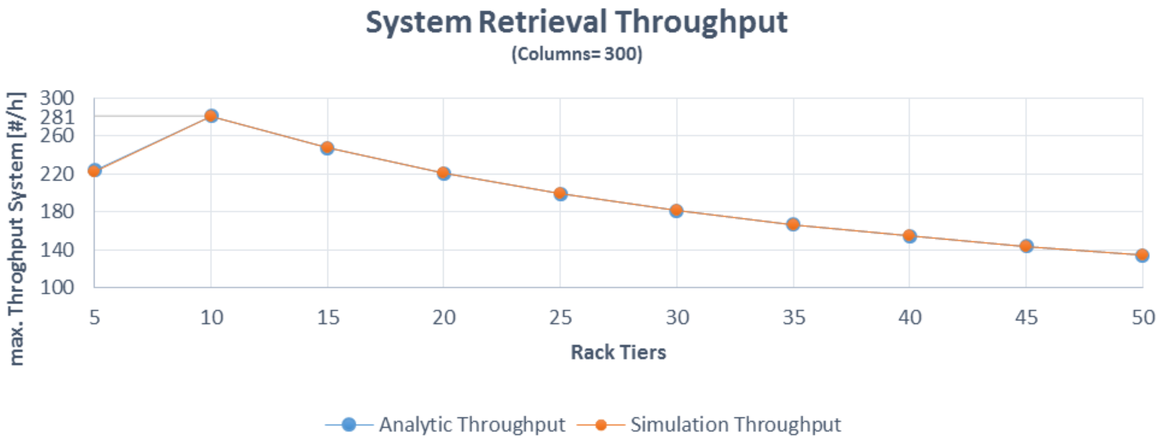

Figure 4-7: System throughput characteristic curve for constant number of columns

4.4.2 Combined processes

In this section, the flow of a single box is listed in order to verify the correctness of the single steps. The verification method is the trace analysis. The simulation outcome is compared with the analytic results. The input data for the combined processes verification are shown in Figure 4-8.

$$v_{maxSh} = 2{,}5\ \frac{m}{s}\ \ (max. velocity\ shuttle)$$

$$v_{maxLi} = 1\ \frac{m}{s}\ \ (max. velocity\ lift)$$

$$a^{+}{}_{Sh} = 1\ \frac{m}{s^2}\ (\dots Acceleration\ shuttle)$$

$$a^{-}{}_{Sh} = 1\ \frac{m}{s^2}\ (\dots Deceleration\ shuttle)$$

$$a^{+}{}_{Li} = 1\ \frac{m}{s^2}\ (\dots Acceleration\ lift)$$

$$a^{-}{}_{Li} = 1\ \frac{m}{s^2}\ (\dots Deceleration\ lift)$$

$$W = 0{,}55\ m\ (\dots Column\ width)$$

$$H = 0{,}35\ m\ (\dots Tier\ height)$$

$$t_{buffer} = 1{,}5s\ (\dots Buffer\ transfer\ time)$$

$$t_{zSh} = 3{,}5s\ \ (\dots \text{Shuttle cycle time in z}-\text{direction})$$

$$t_{0Sh} = 0{,}5s\ \ (\dots Shuttle\ \text{dead time proportion})$$

$$t_{zd} = 1s\ \ (\dots \text{Shuttle cycle time in z-direction for multiple-deep rack}$$

$$t_{zLi} = 1{,}5s\ \ (\dots \text{Lift cycle time in z}-\text{direction})$$

$$t_{0Li} = 0{,}5s\ (\dots \text{Lift dead time proportion})$$

Figure 4-8: Input data for combined processes

Retrieve box

Box no. 1230 is retrieved from the rack. The single action for retrieving a box and the corresponding times are stored during the simulation. The cycle time from the simulation is then compared with the analytic cycle time. Table 4-6 and Table 4-7 illustrate the verification for retrieving a single box. The simulation outcome is displayed in the left column of the tables. There the single steps during the retrieval process are listed. In the right column the analytic calculation is found. The analytic cycle times correspond to the simulation cycle times. Thus, the tool is calculating a single retrieval process correctly.

Retrieval and relocation of a box

In this scenario box no. 1231 shall be retrieved from the rack but this box is obstructed by the box no. 1169. Therefore the obstructing box (box no.1169) has to be relocated before the target box (box no. 1231) can be retrieved. Table 4-8 to Table 4-10 illustrates this process. In the left column of the tables the simulation outcome is displayed. There the single steps with the corresponding cycle times are listed. In the right column the analytic calculation is shown. The cycle times for retrieval and relocation of a box during the simulation are identical with the analytic cycle times for fulfilling the same action. Consequently the tool is calculating the processes correctly.

Simulation outcome		Analytic calculation

Shuttle actual position:	0
Shuttle target position:	30
Shuttle time before movement:	10995,80 [s]
Movement time:	9,10 [s]
Shuttle retrieves box from rack	
Box Name:	Box1230
Actual tier:	7
Actual column:	30
Actual storage depth:	1
Actual time:	11004,90 [s]
Time unloading from rack:	8,00 [s]
Shuttle target position:	0
Shuttle time before movement:	11012,90 [s]
Movement time:	9,10 [s]
Shuttle stores box into retrieval buffer	
Shuttle actual position:	buffer retrieval
Time to store into buffer:	1,50 [s]
Box Name:	Box1230
Actual tier:	7
Actual time:	11123,91 [s]
Shuttle cycle time:	27,70 [s]
Analytic shuttle cycle time:	27,70 [s]

Move to target position

$$s_1 = 30\ columns\ * W = 16{,}5m \qquad \frac{v^2_{maxSh}}{a_{Sh}} = 6{,}25m$$

$$s_1 > \frac{v^2_{maxSh}}{a_{Sh}} \rightarrow Trapezoid\ behavior$$

$$t(s_1) = \frac{16{,}5}{2{,}5} + \frac{2{,}5}{1} = 9{,}1s$$ (Equation 2-4)

Retrieve box from singel deep rack

$$t_{srSh} = 2 * 3{,}5 + 1 = 8s$$ (Equation 3-6)

Move to buffer position

$$s_2 = 30\ columns\ * W = 16{,}5m \qquad \frac{v^2_{maxSh}}{a_{Sh}} = 6{,}25m$$

$$s_2 > \frac{v^2_{maxSh}}{a_{Sh}} \rightarrow Trapezoid\ behavior$$

$$t(s_2) = \frac{16{,}5}{2{,}5} + \frac{2{,}5}{1} = 9{,}1s$$ (Equation 2-4)

Store into buffer

$$t_{buffer} = 1{,}5s$$

Total shuttle cylce time

$$\boxed{T_{sh} = t(s_1) + t_{srSh} + t(s_2) + t_{Buffer} = 27{,}7s}$$

Table 4-6: Retrieval of a box - 1

Simulation outcome	Analytic calculation

Lift actual position:	0
Lift target position:	7
Lift time before movement:	11243,57 [s]
Movement time:	3,45 [s]
Lift retrieves box from retrieval buffer	
Box Name:	Box1230
Lift actual position:	7
Actual time:	11247,02 [s]
Lift loading time:	3,50 [s]
Lift target position:	0
Lift time before movement:	11250,52 [s]
Movement time:	3,45 [s]
Lift actual position:	0
Lift unloads box to I/O - Position	
Lift loading time:	3,50 [s]
Box Name:	Box1230
Actual position:	I/O Position
Actual tier:	0
Actual time:	11257,47 [s]
Lift cycle time:	13,90 [s]
Analytic lift cycle time	13,90 [s]

$$Move\ to\ target\ position$$

$$s_3 = 7\ tiers * H = 2{,}45m \qquad \frac{v_{maxLi}^2}{a_{Li}} = 1m$$

$$s_3 > \frac{v_{maxLi}^2}{a_{Li}} \rightarrow Trapezoid\ behavior$$

$$t(s_3) = \frac{2{,}45}{1} + \frac{1}{1} = 3{,}45s \qquad \text{(Equation 2-4)}$$

$$Lift\ retrives\ box\ from\ buffer$$

$$t_{srLi} = 2 * 1{,}5 + 0{,}5 = 3{,}5s \qquad \text{(Equation 3-8)}$$

$$Move\ to\ output\ position$$

$$s_4 = 7\ tiers * H = 2{,}45m \qquad \frac{v_{maxLi}^2}{a_{Li}} = 1m$$

$$s_4 > \frac{v_{maxLi}^2}{a_{Li}} \rightarrow Trapezoid\ behavior$$

$$t(s_4) = \frac{2{,}45}{1} + \frac{1}{1} = 3{,}45s \qquad \text{(Equation 2-4)}$$

$$Lift\ unloads\ box\ to\ output\ position$$

$$t_{srLi} = 2 * 1{,}5 + 0{,}5 = 3{,}5s \qquad \text{(Equation 3-8)}$$

$$Total\ lift\ cylce\ time$$

$$\boxed{T_{sh} = t(s_3) + t_{srLi} + t(s_4) + t_{srLi} = 13{,}9s}$$

Table 4-7: Retrieval of a box - 2

Simulation outcome		Analytic calculation

Box Name:	Box1231
Shuttle actual position:	0
Shuttle target position:	91
Shuttle time before movement:	3009,40
Movement time:	22,52 [s]
Relocation of Box Nr.:	Box1169
Shuttle actual position:	91
Time unloading from rack:	8 [s]
Shuttle actual position:	91
Shuttle target position:	92
Shuttle time before movement:	3039,92 [s]
Movement time:	1,48 [s]
Shuttle actual position:	92
Time storing in rack:	8 [s]

Moving to target position

$$s_1 = 91\ columns * W = 50{,}5m \qquad \frac{v_{maxSh}^2}{a_{Sh}} = 6{,}25m$$

$$s_1 > \frac{v_{maxSh}^2}{a_{Sh}} \rightarrow Trapezoid\ behavior$$

$$\underline{\underline{t(s_1) = \frac{50{,}5}{2{,}5} + \frac{2{,}5}{1} = 22{,}52s}} \qquad \text{(Equation 2-4)}$$

Retrieving from singel deep rack

$$\underline{\underline{t_{srSh} = 2 * 3{,}5 + 1 = 8s}} \qquad \text{(Equation 3-6)}$$

Relocation of obstructing box

$$s_2 = 1\ column * W = 0{,}55m \qquad \frac{v_{maxSh}^2}{a_{Sh}} = 6{,}25m$$

$$s_2 < \frac{v_{maxSh}^2}{a_{Sh}} \rightarrow Triangular\ behavior$$

$$\underline{\underline{t(s_2) = 2 * \sqrt{\frac{0{,}55}{1}} = 1{,}48s}} \qquad \text{(Equation 2-2)}$$

Storing in singel deep rack

$$\underline{\underline{t_{srSh} = 2 * 3{,}5 + 1 = 8s}} \qquad \text{(Equation 3-6)}$$

Table 4-8: Retrieval and relocation of a box - 1

Simulation outcome	
Shuttle actual position:	92
Shuttle target position:	91
Shuttle time before movement:	3049,40 [s]
Movement time:	1,48 [s]
Retrieve initial box	
Box Name:	Box1231
Actual tier:	6
Actual column:	91
Actual storage depth:	2
Actual time:	3050,88 [s]
Shuttle actual position:	91
Time unloading from rack:	10,00 [s]
Shuttle actual position:	91
Shuttle target position:	0
Shuttle time before movement:	3060,88 [s]
Movement time:	22,52 [s]
Shuttle actual position:	0
Time to store into buffer:	1,5 [s]
Shuttle stores box into retrieval buffer	
Box Name:	Box1231
Actual position:	buffer retrieval
Actual tier:	6
Actual time:	3137,51 [s]
Shuttle cycle time:	75,51 [s]
Analytic shuttle cycle time:	75,51 [s]

Analytic calculation

Moving back to target position

$$s_3 = 1\ column * W = 0{,}55m \qquad \frac{v_{maxSh}^2}{a_{Sh}} = 6{,}25m$$

$$s_3 < \frac{v_{maxSh}^2}{a_{Sh}} \rightarrow Triangular\ behavior$$

$$t(s_3) = 2 * \sqrt{\frac{0{,}55}{1}} = 1{,}48s \qquad \text{(Equation 2-2)}$$

Retrieve initial box, double deep rack

$$t_{srSh_m} = 2 * 3{,}5 + 2 * 1 + 1 = 10s \qquad \text{(Equation 3-7)}$$

Moving to buffer position

$$s_4 = 91\ columns * W = 50{,}5m \qquad \frac{v_{maxSh}^2}{a_{Sh}} = 6{,}25m$$

$$s_4 > \frac{v_{maxSh}^2}{a_{Sh}} \rightarrow Trapezoid\ behavior$$

$$t(s_4) = \frac{50{,}5}{2{,}5} + \frac{2{,}5}{1} = 22{,}52s \qquad \text{(Equation 2-4)}$$

Store into buffer

$$t_{buffer} = 1{,}5s$$

Total shuttle cylce time

$$\boxed{\begin{array}{l} T_{sh} = t(s_1) + t_{srSh} + t(s_2) + t_{srSh} + t(s_3) + t_{srSh_m} + t(s_4) + t_{Buffer} \\ T_{sh} = 75{,}51s \end{array}}$$

Table 4-9: Retrieval and relocation of a box - 2

Simulation outcome	
Lift actual position:	0
Lift target position:	6
Lift time before movement:	3257,52
Movement time:	3,10 [s]
Box Name:	Box1231
Actual tier:	6
Actual time:	3260,62 [s]
Lift retrieves box from retrieval buffer	
Lift actual position:	6
Lift loading time:	3,50 [s]
Lift actual position:	6
Lift target position:	0
Lift time before movement:	3264,12 [s]
Movement time:	3,10 [s]
Lift actual position:	0
Lift unloads box to O-Position	
Lift loading time:	3,50 [s]
Box Name:	Box1231
Actual position:	O-Position
Actual tier:	0
Actual time:	3270,72 [s]
Lift cycle time:	13,20 [s]
Analytic lift cycle time:	13,20 [s]

Analytic calculation

Move to target position

$s_5 = 6\ tiers * H = 2{,}1m \qquad \frac{v_{maxLi}^2}{a_{Li}} = 1m$

$s_5 > \frac{v_{maxLi}^2}{a_{Li}} \rightarrow Trapezoid\ behavior$

$$t(s_5) = \frac{2{,}1}{1} + \frac{1}{1} = 3{,}1s \qquad \text{(Equation 2-4)}$$

Lift retrives box from buffer

$$t_{srLi} = 2 * 1{,}5 + 0{,}5 = 3{,}5s \qquad \text{(Equation 3-8)}$$

Move to output position

$s_6 = 6\ tiers * H = 2{,}1m \qquad \frac{v_{maxLi}^2}{a_{Li}} = 1m$

$s_6 > \frac{v_{maxLi}^2}{a_{Li}} \rightarrow Trapezoid\ behavior$

$$t(s_6) = \frac{2{,}1}{1} + \frac{1}{1} = 3{,}1s \qquad \text{(Equation 2-4)}$$

Lift unloads box to output position

$$t_{srLi} = 2 * 1{,}5 + 0{,}5 = 3{,}5s \qquad \text{(Equation 3-8)}$$

Total lift cylce time

$$\boxed{T_{sh} = t(s_5) + t_{srLi} + t(s_6) + t_{srLi} = 13{,}2s}$$

Table 4-10: Retrieval and relocation of a box - 3

4.4.3 Rack occupancy

The rack is occupied randomly with boxes. The boxes should be distributed uniform over the rack. With the sub model testing the uniform distribution of boxes is verified. The uniform distribution can be checked by the number of boxes per tier (Figure 4-9) and the number of boxes per column (Figure 4-10). Figure 4-9 and Figure 4-10 are occupancy distributions for a rack with 10 tiers and 100 columns.

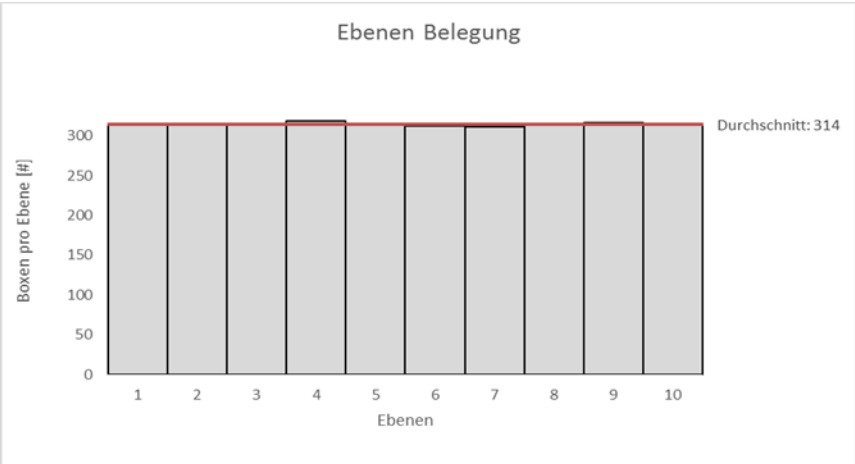

Figure 4-9: Number of boxes per tier

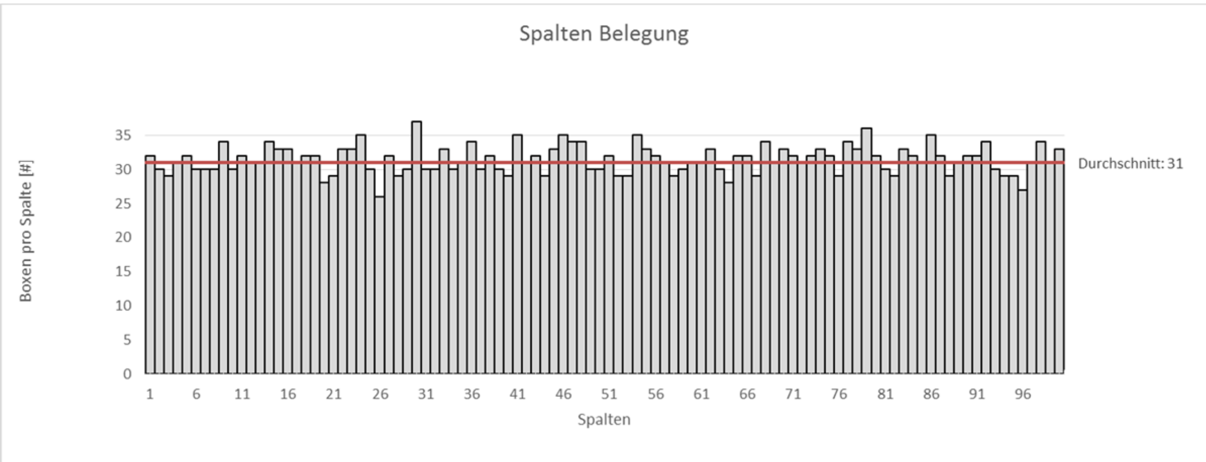

Figure 4-10: Number of boxes per column

Random rack occupancy

The quality of the random rack occupancy may also depend on the rack size. Therefore some rack configuration scenarios are defined to examine the rack occupancy. The scenarios with their configuration are displayed in Figure 4-11.

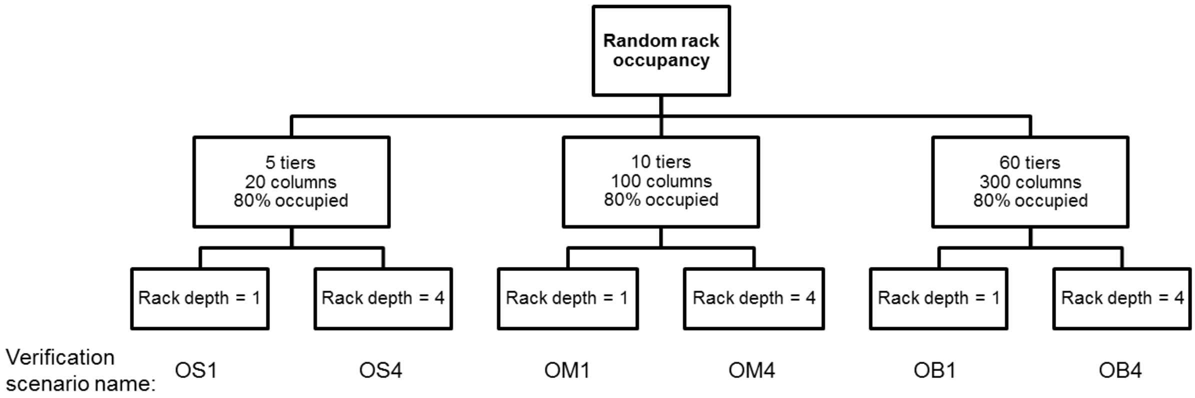

Figure 4-11: Rack occupancy scenarios

For each scenario the rack occupancy is examined in order to verify the uniform distribution of the rack. The distribution over the tiers and the distribution over the columns are investigated. To verify a uniform distribution, the Chi-square test (Chapter 2.2.1) has been carried out. In Table 4-11 the outcome of the scenario investigation is summarized. For each scenario the rack occupancy over the columns and the rack occupancy over the tiers are uniform distributed. Thus the tool is occupying the rack correctly.

Sceanrio name	Occupation over columns			Occupation over tiers		
	Chi-square test value	0,95 Quantil	Outcome	Chi-square test value	0,95 Quantil	Outcome
OS1	4,56	30,14	uniform distributed	0,21	9,49	uniform distributed
OS4	1,99	30,14	uniform distributed	0,14	9,49	uniform distributed
OM1	16,33	123,23	uniform distributed	1,99	16,92	uniform distributed
OM4	17,63	123,23	uniform distributed	1,60	16,92	uniform distributed
OB1	35,33	340,33	uniform distributed	22,22	77,93	uniform distributed
OB4	47,28	340,33	uniform distributed	57,32	77,93	uniform distributed

Table 4-11: Outcome rack occupancy verification

Random rack occupancy from behind

In Figure 4-12 the number of boxes over the rack depth is displayed. In this case the rack is randomly occupied. In comparison, Figure 4-13 illustrates the box distribution over the rack depth when the rack is occupied from behind. There the deeper layers contain more boxes than the first layer. In both cases the rack is four layers deep.

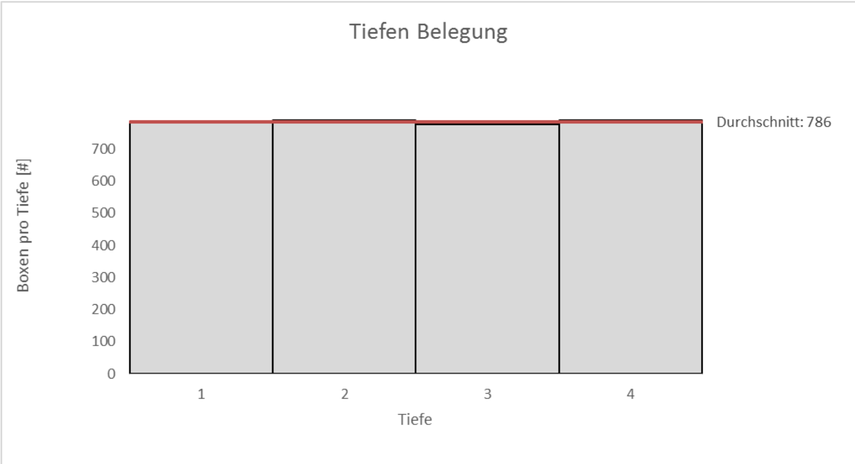

Figure 4-12: Number of boxes per rack depth

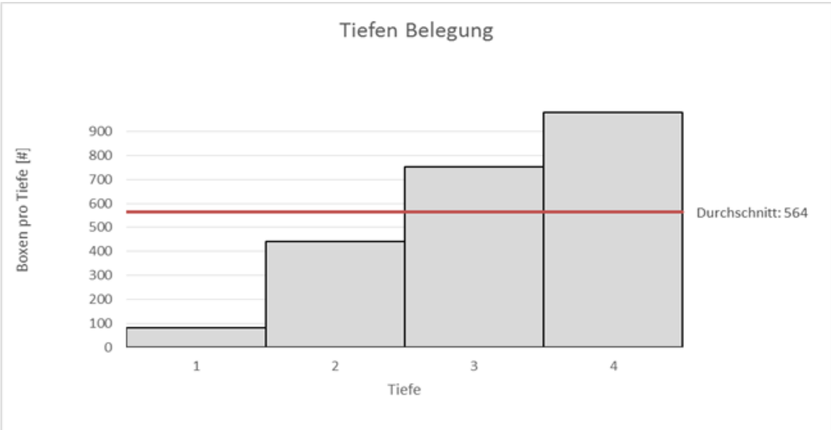

Figure 4-13: Number of boxes per rack depth when occupied from behind

To verify the rack occupancy from behind some verification scenarios are created (Figure 4-14). For each scenario the box distribution over columns and the box distribution over tiers are examined.

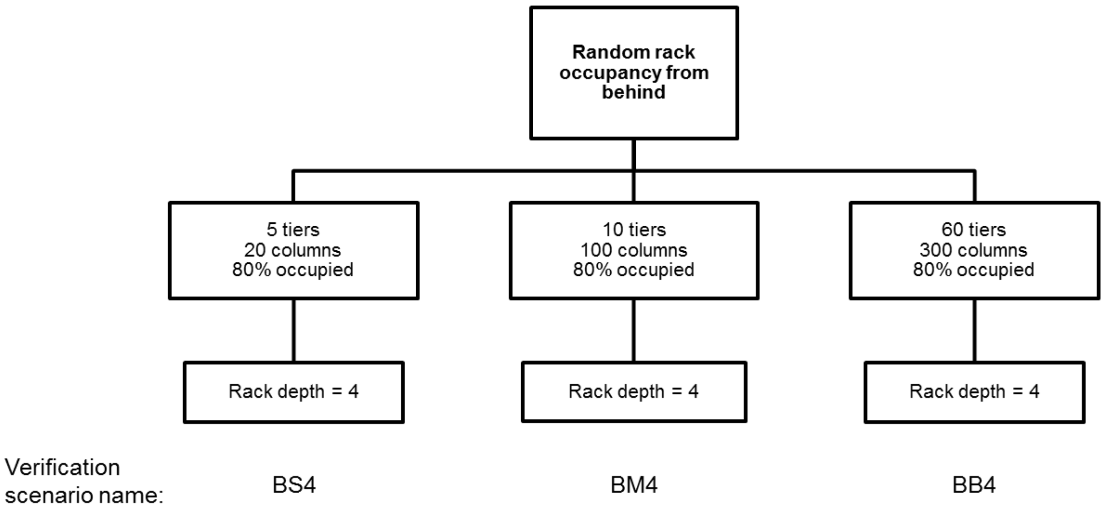

Figure 4-14: Rack occupancy from behind scenarios

For each scenario the order distribution should be uniform. To test the uniform distribution, the Chi-square test (Chapter 2.2.1) is carried out. The outcome of the investigation is summarized in Table 4-12. For each scenario the rack occupancy is uniform distributed. Consequently the strategy to occupy the rack from behind is working correctly.

Sceanrio name	Occupation over columns			Occupation over tiers		
	Chi-square test value	0,95 Quantil	Outcome	Chi-square test value	0,95 Quantil	Outcome
BS4	3,49	30,14	uniform distributed	0,58	9,49	uniform distributed
BM4	19,45	123,23	uniform distributed	2,12	16,92	uniform distributed
BB4	45,93	340,33	uniform distributed	65,62	77,93	uniform distributed

Table 4-12: Outcome rack occupancy from behind verification

4.4.4 Orders

During a simulation run, the model is creating the orders randomly. These orders are then processed in a certain way. The random order creation and the order handling are investigated below.

Random order creation

The orders are created randomly with the Excel function RND(). The created orders should be uniform distributed. In the following the uniform distribution of the orders is examined. Therefore six verification scenarios are created (Figure 4-15). These scenarios differ by the rack dimensions.

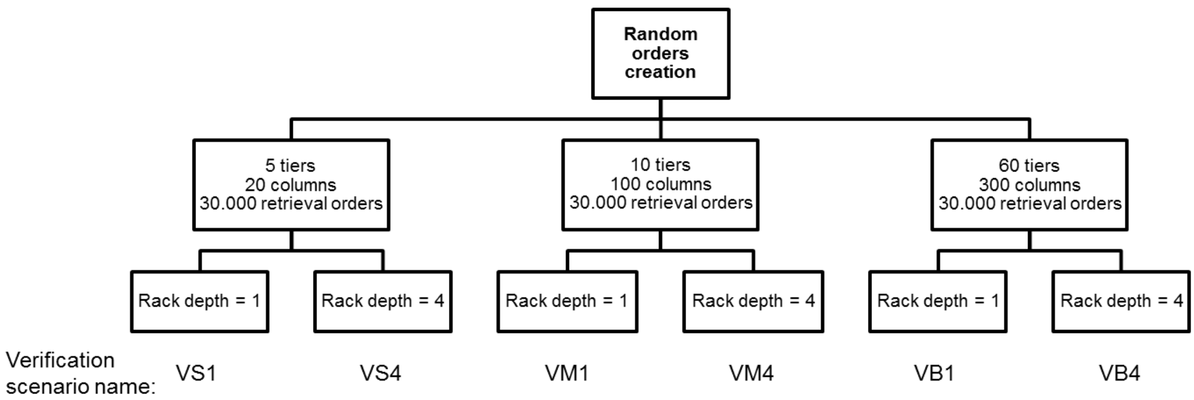

Figure 4-15: Random order creation scenarios

The distribution of the order proportion over the rack columns and the distribution of the order proportion over the rack tiers are examined for each scenario. With the Chi-square test the distributions are tested if they are uniform. The outcomes of these tests are summarized in Table 4-13. Only with the largest rack configuration (scenario VB4) the orders are uniform distributed. In all the other scenarios the orders are not uniform distributed. Thus the tool is not creating the orders sufficient. This situation is discussed in chapter 5 (Conclusion).

Sceanrio name	Order proportion over columns			Order proportion over tiers		
	Chi-square test value	0,95 Quantil	Outcome	Chi-square test value	0,95 Quantil	Outcome
VS1	3012,82	30,14	not uniform distributed	210,55	9,49	not uniform distributed
VS4	1219,29	30,14	not uniform distributed	18,61	9,49	not uniform distributed
VM1	1643,36	123,23	not uniform distributed	137,09	16,92	not uniform distributed
VM4	859,92	123,23	not uniform distributed	15,53	16,92	uniform distributed
VB1	505,73	340,33	not uniform distributed	30,73	77,93	uniform distributed
VB4	262,75	340,33	uniform distributed	17,30	77,93	uniform distributed

Table 4-13: Outcome random order creation verification

Order handling

To verify the order handling the trace analysis is carried out. The orders are tracked during the simulation and additional information about the handling is obtained. Table 4-14 illustrates en excerpt of all the orders and their corresponding information. Thus an order implies

- the name of the box (1)
- the handling action (store/retrieve) (2)
- the start time of the order (3)
- the end time of the order (4)
- the start position (5)
- the end position (6)

and other specific information. It can be seen that the orders are handled correctly. The process of the order handling is consistent thus the tool is handling the orders correct.

1	2	3	4				5	6		
Datum:	18.05.2015		itel:	Betriebspunkt 1						
Box Nr.	Aktion [Einlagern/Auslagern	Startzeit [s]	Endzeit [s]	Zyklus Zeit [s]	Start Gewerk [Shuttle / Lift]	End Gewerk [Shuttle / Lift]	Start Position	End Position	Wartezeit auf Puffer [s]	Gesamte Wartezeit [s]
Box4507	Einlagern	913,61	962,34	48,73	Lift Nr. 1	Shuttle Nr. 9	Einlager-Pos. 0	Ebene: 9 Spalte: 1	0,00	25,30
Box4535	Auslagern	522,94	973,08	450,14	Shuttle Nr. 6	Lift Nr. 1	Ebene: 6 Spalte: 24	Auslager-Pos. Nr: 0	55,72	401,22
Box4536	Auslagern	531,37	1000,94	469,57	Shuttle Nr. 4	Lift Nr. 1	Ebene: 4 Spalte: 88	Auslager-Pos. Nr: 0	14,90	359,05
Box4505	Einlagern	981,99	1013,34	31,34	Lift Nr. 1	Shuttle Nr. 4	Einlager-Pos. 0	Ebene: 4 Spalte: 1	0,00	5,00
Box4537	Auslagern	533,75	1019,16	485,41	Shuttle Nr. 7	Lift Nr. 1	Ebene: 7 Spalte: 45	Auslager-Pos. Nr: 0	65,65	416,80
Box4528	Auslagern	419,66	1028,78	609,13	Shuttle Nr. 3	Lift Nr. 1	Ebene: 3 Spalte: 10	Auslager-Pos. Nr: 0	223,16	574,32
Box4508	Einlagern	1000,94	1033,25	32,32	Lift Nr. 1	Shuttle Nr. 7	Einlager-Pos. 0	Ebene: 7 Spalte: 1	0,00	9,29
Box4494	Einlagern	876,22	1039,39	163,16	Lift Nr. 1	Shuttle Nr. 3	Einlager-Pos. 0	Ebene: 3 Spalte: 1	0,00	140,94
Box4534	Auslagern	549,31	1041,21	491,90	Shuttle Nr. 10	Lift Nr. 1	Ebene: 10 Spalte: 59	Auslager-Pos. Nr: 0	86,62	437,77
Box4498	Einlagern	836,34	1051,00	214,66	Lift Nr. 1	Shuttle Nr. 10	Einlager-Pos. 0	Ebene: 10 Spalte: 2	0,00	190,44
Box4539	Auslagern	584,98	1052,84	467,86	Shuttle Nr. 8	Lift Nr. 1	Ebene: 8 Spalte: 57	Auslager-Pos. Nr: 0	35,90	387,05

Table 4-14: Excerpt of the order handling verification

4.4.5 Order list

To ensure that the order list is processed correctly, the fulfilled orders are examined. Table 4-15 shows the excerpt from an order list. For each order, the name of the box, the box location (tier, column, depth), and the handling action (store/retrieve) is listed. The orders shall be processed in the sequence as they are listed. To verify the handling of the order list, the trace analysis is carried out. The outcome of the trace analysis is shown in Table 4-16. In this table the fulfilled orders are listed. An order implies

- the name of the box (1)
- the start time of the order (2)
- the end time of the order (3)
- the start position (4)
- the end position (5)

and other specific information. The model is fulfills the order sequence from the order list correctly. Also the retrieval orders from the order list are carried out properly. Orders which have to be stored into the rack are delivered to the specified tier, but not to the specified column. The reason therefore is that the shuttle is storing the box in the nearest empty bay in order to minimize the transportation way. Overall, the processing of the order list is sufficient.

Auftragsliste Soll				
Box Nr.	Ebene	Fach	Tiefe	Aktion [Einlagern/Auslagern]
Box203	1	53	2	Auslagern
Box344	2	100	4	Einlagern
Box491	3	65	4	Auslagern
Box861	4	31	2	Einlagern
Box1056	5	69	2	Auslagern
Box1299	6	7	2	Einlagern
Box1495	7	47	2	Auslagern
Box1760	8	25	1	Einlagern
Box1823	9	36	4	Auslagern
Box2100	10	31	3	Einlagern

Table 4-15: Excerpt from an order list

1	2	3				4	5			
Ausführung der Auftragsliste										
Box Nr.	Startzeit [s]	Endzeit [s]	Relativ Zeit [s]	Start Gewerk [Shuttle / Lift]	End Gewerk [Shuttle / Lift]	Start Position	End Position	Zeit in Puffer bis Auftrag Annahme [s]	Gesamte Wartezeit [s]	Anzahl Umlagerungen [#]
Box203	0,00	80,01	80,01	Shuttle Nr. 1	Lift Nr. 1	Ebene: 1 Spalte: 53	Auslager-Pos. Nr: 0	0,76	0,76	0
Box344	80,01	106,00	25,98	Lift Nr. 1	Shuttle Nr. 2	Einlager-Pos. 0	Ebene: 2 Spalte: 1	0,00	0,00	0
Box491	0,00	97,15	97,15	Shuttle Nr. 3	Lift Nr. 1	Ebene: 3 Spalte: 65	Auslager-Pos. Nr: 0	9,34	9,34	0
Box861	97,15	119,57	22,43	Lift Nr. 1	Shuttle Nr. 4	Einlager-Pos. 0	Ebene: 4 Spalte: 1	0,00	0,00	0
Box1056	0,00	115,13	115,13	Shuttle Nr. 5	Lift Nr. 1	Ebene: 5 Spalte: 69	Auslager-Pos. Nr: 0	18,92	18,92	0
Box1299	115,13	143,96	28,83	Lift Nr. 1	Shuttle Nr. 6	Einlager-Pos. 0	Ebene: 6 Spalte: 1	0,00	0,00	0
Box1495	0,00	133,92	133,92	Shuttle Nr. 7	Lift Nr. 1	Ebene: 7 Spalte: 47	Auslager-Pos. Nr: 0	59,30	59,30	0
Box1760	133,92	159,14	25,23	Lift Nr. 1	Shuttle Nr. 8	Einlager-Pos. 0	Ebene: 8 Spalte: 1	0,00	0,00	0
Box1823	108,07	153,50	45,43	Shuttle Nr. 9	Lift Nr. 1	Ebene: 9 Spalte: 36	Auslager-Pos. Nr: 0	3,00	3,00	3
Box2100	153,50	177,13	23,63	Lift Nr. 1	Shuttle Nr. 10	Einlager-Pos. 0	Ebene: 10 Spalte: 1	0,00	0,00	0

Table 4-16: Excerpt from the fulfilled order list

4.4.6 Batch size

With the function 'order sequencing' the orders are handled batch wise. Each batch has a certain size, which means it consists of a certain number of boxes. There are three possibilities to define the batch size:

- Constant number of boxes within a batch
- Uniform distributed batch size. The batch size is than defined with a lower and upper limit
- Normal distributed batch size. In this case, the size is defined by the mean value and the standard deviation

In the following it is verified if the model is creating the batch size correctly

Constant batch size

An excerpt from all the created batches during the simulation is shown in Table 4-17. It illustrates the batch size and the boxes which it is composed of. It can be seen that the batch size is constant. In this case each batch consists of three boxes.

				Anzahl der Lose:	334		
				Durchschnittliche Anzahl der Boxen pro Los:	3,00		
Los Nr.	Boxen pro Los [#]	Los					
1	3	Box617	Box840	Box365			
2	3	Box1171	Box132	Box625			
3	3	Box545	Box847	Box55			
4	3	Box559	Box213	Box439			
5	3	Box289	Box951	Box392			
6	3	Box267	Box103	Box609			
7	3	Box978	Box275	Box190			
8	3	Box209	Box521	Box637			
9	3	Box170	Box755	Box247			
10	3	Box878	Box1106	Box988			

Table 4-17: Outcome constant batch size

Uniform distributed batch size

In order to verify the uniform distributed batch size the sub model testing is carried out. In this case 24.964 batches are created. The minimum batch size is two and the maximum batch size is six. Figure 4-16 shows the distribution of the created batches. It illustrates the batch size in relation to the proportion of all the fulfilled orders.

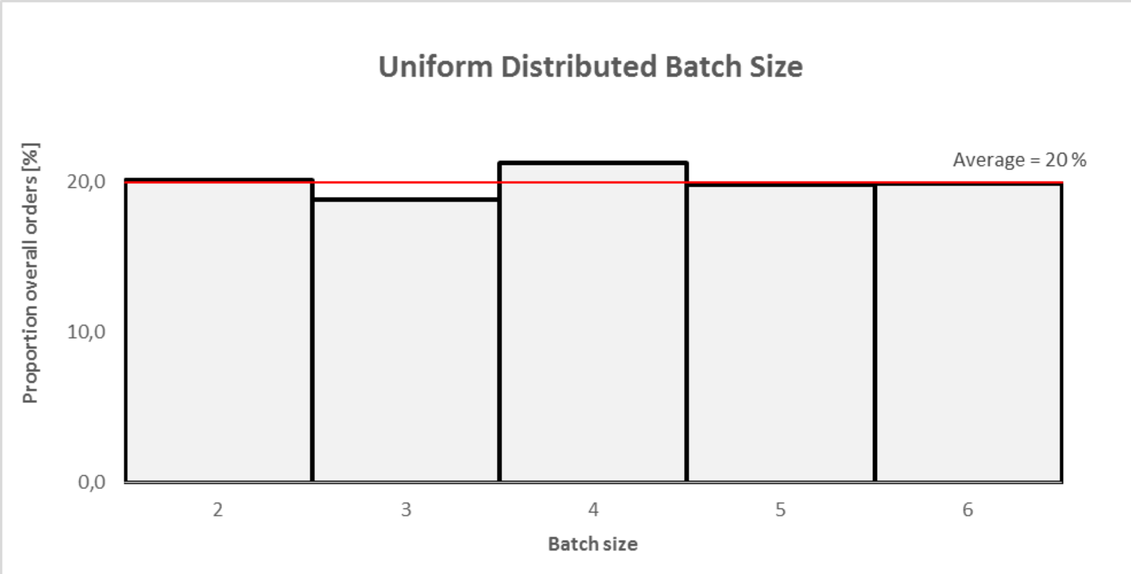

Figure 4-16: Outcome uniform distributed batch size

The Chi-square test is carried out to test if the distribution is uniform.

H_0… The batch size is uniform distributed
H_1…The batch size is not uniform distributed

Test value χ^2

$$\chi^2 = \sum_{i=1}^{n} \frac{(h_i - h_E)^2}{h_E} \qquad \text{(Equation 2-5)}$$

Expected value h_E = 4992,8

In Table 4-18 the empirical frequencies (h_i) and the Chi-square test value are displayed.

i	hi	(hi-hE)^2/hE
1	5024	0,195
2	4705	16,590
3	5310	20,152
4	4952	0,333
5	4973	0,079
		Sum= 37,349

Table 4-18: Chi-square test for uniform distributed batch size

χ^2 *test value* = 37,349 (= sum of the normalized deviation)
${\chi^2}_{0,95(4)} = 9{,}49$ (0,95 *Quantil with* 4 *degrees of freedom*: $k = 5 - 1$)

$37{,}349 > 9{,}49 \rightarrow reject\ H_0$

The batch size is not uniform distributed. With the function 'order sequencing' and 'uniform distributed batch size', the model is not creating the batch size correct. It is required that the batches size is uniform distributed but the Chi-square test revealed that the batch size distribution is not uniform. When the batch size is larger (more boxes within a batch) it is more likely that the batch size is uniform distributed.

Normal distributed batch size

To verify if the batch size is normal distributed, the sub model test is used. Therefore 24.966 batches are created. The mean value is four and the standard deviation is one. Figure 4-17 illustrates the batch size in relation to the proportion of all the fulfilled orders.

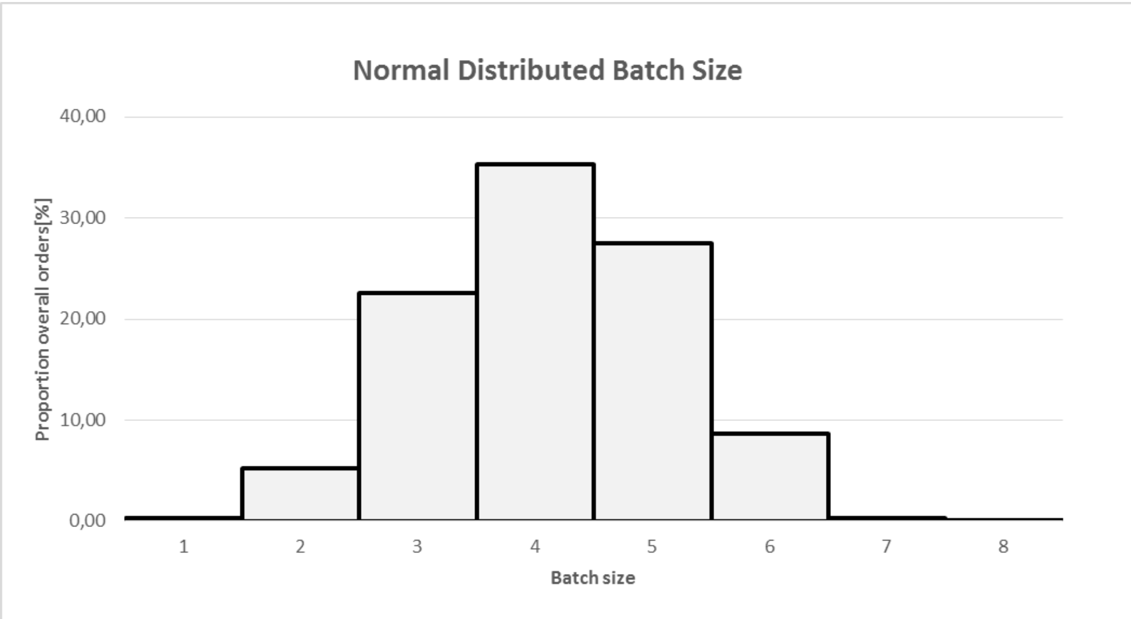

Figure 4-17: Outcome normal distributed batch size

The Anderson-Darling test is carried out to test if the batch size distribution is normal distributed.

H_0… The batch size is normal distributed
H_1…The batch size is not normal distributed

Test statistics AD^2

$$AD^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\left[\ln\left(F_0(x_i)\right) + \ln(1 - F_0(x_{n-i+1}))\right] \qquad \text{(Equation 2-7)}$$

$\textbf{Critical value (Confidence level } = \textbf{95}\%)$

$$AD^2_{\mathrm{n},0.95} = \frac{0.752}{1+\frac{3}{4n}+\frac{9}{4n^2}} \qquad \text{(Equation 2-8)}$$

In Table 4-19 the single terms to calculate the test statistic AD^2 are highlighted.

Number of values: 8
Mean value: 3120,5
Standard deviation: 3492,480

i	xi	F0(xi)	F1 = ln(F0(xi))	F0(xn-i+1)	1-F0(xn-i+1)	F2=ln(1-F0(xn-i+1))	S=F1+F2	S*(2*i-1)
1	7	0,186	-1,680	0,949	0,051	-2,974	-4,655	-4,655
2	77	0,192	-1,652	0,858	0,142	-1,953	-3,605	-10,814
3	89	0,193	-1,647	0,765	0,235	-1,448	-3,095	-15,475
4	1295	0,301	-1,202	0,391	0,609	-0,497	-1,699	-11,890
5	2158	0,391	-0,938	0,301	0,699	-0,358	-1,295	-11,659
6	5644	0,765	-0,268	0,193	0,807	-0,214	-0,482	-5,301
7	6865	0,858	-0,153	0,192	0,808	-0,213	-0,366	-4,756
8	8829	0,949	-0,052	0,186	0,814	-0,206	-0,259	-3,879
								Sum= -68,429

Table 4-19: Anderson-Darling test for normal distributed batch size

$Critical\ value: AD^2_{8,0.95} = 0{,}666$
$Test\ statistics: AD^2 = 0{,}554$
$0{,}666 > 0{,}554 \rightarrow accept\ H_0$

The batch size is normal distributed. When the function ‘order sequencing’ and ‘normal distributed batch size’ is selected, the model creates the batch size correctly. This is also valid for batches with a different mean value and different standard deviation.

4.4.7 ABC- distribution

To apply the ABC- distribution, the model is sectioning the rack into A-.B- and C- sections. With the sub model testing, it is tested if the model is sectioning the rack correctly. Depending on the rack size the quality of this sectioning may vary. Because of this, for each possibly ABC arrangement two scenarios are examined. One with ‘small’ rack dimension (five tiers and 20 columns) and the other scenario with ‘large’ rack dimension (60 tiers, 300 columns).

'Block' rack occupancy

With the 'block' occupancy, the rack is sectioned into blocks. Table 4-20 and Table 4-21 illustrate the outcome of the 'block' rack occupancy. With the 'large' rack configuration (Table 4-21) the model is sectioning the rack accurately. For the 'small' rack configuration the target values are not achieved. In this case 20% of the rack shall be allocated for A-goods but actually the model is allocating 41,6% to A-goods. This difference between the target rack occupancy and the actual rack occupancy occurs because the model is sectioning the rack into rectangular sections. When creating these sections, the numbers of compartments in a section are rounded down in order to achieve even rectangular sections.

Input	Amount tiers:	5 [#]
	Amount columns:	20 [#]
	ABC-distribution:	"Block"
	A- proportion:	20,0 [%]
	B- proportion:	30,0 [%]
	C- proportion:	50,0 [%]
Output	A- proportion:	41,6 [%]
	B- proportion:	26,9 [%]
	C- proportion:	30,5 [%]
	A-difference:	21,6 [%]
	B-difference:	3,1 [%]
	C-difference:	19,5 [%]

Table 4-20: 'Block' occupancy small

Input	Amount tiers:	60 [#]
	Amount columns:	300 [#]
	ABC-distribution:	"Block"
	A- proportion:	20,0 [%]
	B- proportion:	30,0 [%]
	C- proportion:	50,0 [%]
Output	A- proportion:	20,0 [%]
	B- proportion:	29,3 [%]
	C- proportion:	50,4 [%]
	A-difference:	0,0 [%]
	B-difference:	0,7 [%]
	C-difference:	0,4 [%]

Table 4-21: 'Block' occupancy large

'Column' rack occupancy

Here the rack is sectioned into columns. Table 4-22 and Table 4-23 illustrate the outcome of the 'column' rack occupancy. As with the 'block' rack occupancy, the 'column' rack occupancy for the 'large' rack configuration is accurate. For the 'small' rack configuration even higher differences between the target and actual values occur.

Input	Amount tiers:	5 [#]
	Amount columns:	20 [#]
	ABC-distribution:	"Columns"
	A- proportion:	20,0 [%]
	B- proportion:	30,0 [%]
	C- proportion:	50,0 [%]
Output	A- proportion:	91,1 [%]
	B- proportion:	3,0 [%]
	C- proportion:	5,0 [%]
	A-difference:	71,1 [%]
	B-difference:	27,0 [%]
	C-difference:	45,0 [%]

Table 4-22: 'Column' occupancy small

Input	Amount tiers:	60 [#]
	Amount columns:	300 [#]
	ABC-distribution:	"Columns"
	A- proportion:	20,0 [%]
	B- proportion:	30,0 [%]
	C- proportion:	50,0 [%]
Output	A- proportion:	19,9 [%]
	B- proportion:	29,9 [%]
	C- proportion:	49,8 [%]
	A-difference:	0,1 [%]
	B-difference:	0,1 [%]
	C-difference:	0,2 [%]

Table 4-23: 'Column' occupancy large

'Row' rack occupancy

The rack is sectioned into rows. The outcome of this sectioning is illustrated in Table 4-24 and Table 4-25. Also here, with the 'large' rack configuration the target values are achieved. For the 'small' rack configuration there are large differences between the target value and the actual value.

Input	Amount tiers:	5 [#]
	Amount columns:	20 [#]
	ABC-distribution:	"Rows"
	A- proportion:	20,0 [%]
	B- proportion:	30,0 [%]
	C- proportion:	50,0 [%]
Output	A- proportion:	91,1 [%]
	B- proportion:	2,0 [%]
	C- proportion:	5,9 [%]
	A-difference:	71,1 [%]
	B-difference:	28,0 [%]
	C-difference:	44,1 [%]

Table 4-24: 'Row' occupancy small

Input	Amount tiers:	60 [#]
	Amount columns:	300 [#]
	ABC-distribution:	"Rows"
	A- proportion:	20,0 [%]
	B- proportion:	30,0 [%]
	C- proportion:	50,0 [%]
Output	A- proportion:	19,9 [%]
	B- proportion:	29,9 [%]
	C- proportion:	49,8 [%]
	A-difference:	0,1 [%]
	B-difference:	0,1 [%]
	C-difference:	0,2 [%]

Table 4-25: 'Row' occupancy large

Altogether, when selected an ABC-distribution, the quality of the rack occupancy depends on the size of the rack. With a larger rack (more tiers and more columns), the occupancy is more accurate. The rack depth has no influence on the quality of the ABC- rack occupancy because the model is sectioning the cross-section of the rack and this sectioning is projected into the rack depth.

4.5 Model validation

In this thesis the comparison of the performance data from the software model with the performance data of a real shuttle system was not possible. Therefore the whole simulation has been visualized in order to check validity of the single steps within the simulation. Figure 4-18 shows a screenshot from the visualization. There the rack, buffer and I/O- position is displayed. Depending on which action is carried out at the moment; either the lift or the shuttle is shown. With the visualization, the whole system, lifts, shuttles or a specific box can be tracked. Thus the logical sequence of the single events can be reviewed.
Also the simulation run has been multiple repeated like mentioned in chapter 2.4.6. The visualization and the multiple simulation runs with always the same results lead to the assumption that the model is valid.

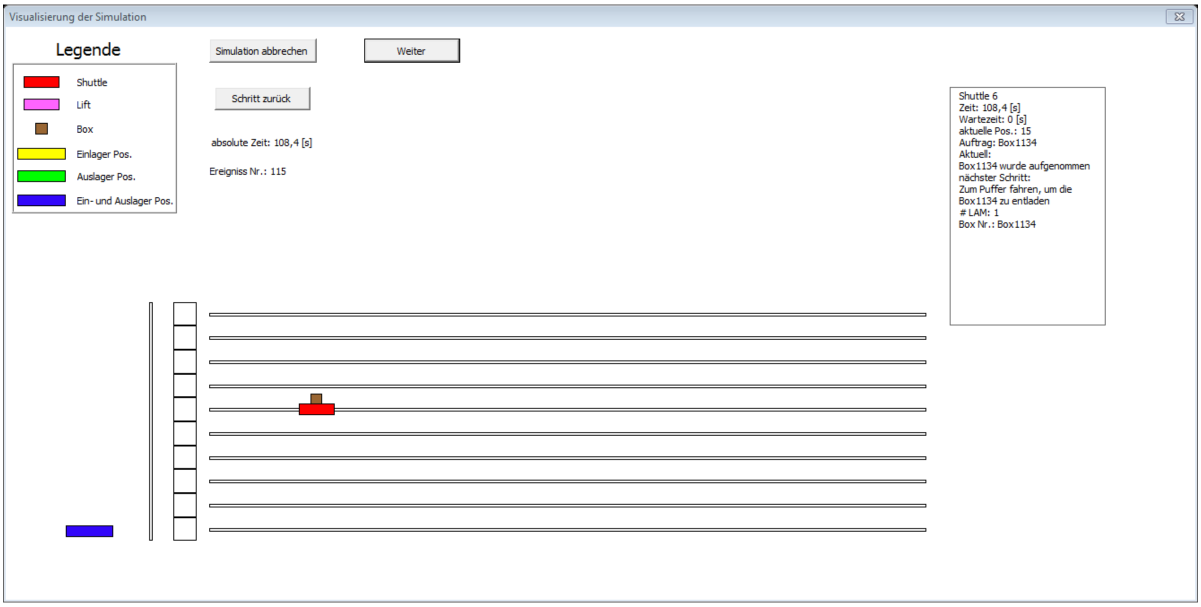

Figure 4-18: Screenshot from the visualization

4.6 Experimental plan for simulation

For further investigation into the model behaviour a series of scenarios with different parameters is set up. Derived from a base scenario, different other scenarios are derived with different parameters. Figure 4-19 illustrates the scenario overview.
Also the actual tool is compared with the initial tool from the Institute of Logistics Engineering.

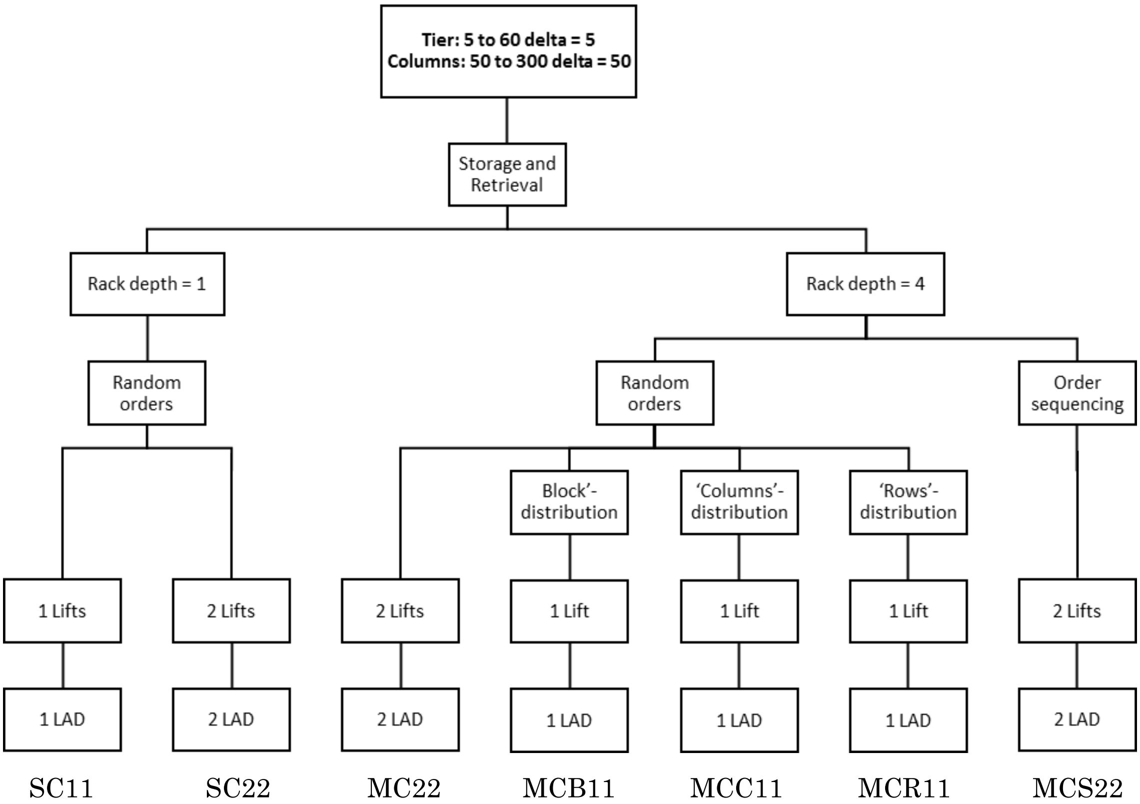

Figure 4-19: Scenarios overview

4.7 Experiments execution

In this phase the scenarios in chapter 4.7 are executed and evaluated. The parameters for each scenario are briefly described, then the results are displayed and at the end a short conclusion concerning the investigated scenario is given.

The scenarios are named as illustrated in Figure 4-19. For each scenario the same rack parameters (Table 4-26), the same kinematic parameters for lift (Table 4-27) and the same kinematic parameters for shuttle (Table 4-28) are set. Further system specifications are:

- Storage and retrieval orders
- 50.000 orders per simulation run
- Rack occupancy is constant
- I/O- position located on the first tier
- Buffer capacity is one

Breite Fach	2600	[mm]
Höhe Fach	350	[mm]
Länge (x)	312	[m]
Höhe (y)	10,5	[m]
Maximale Pufferkapazität	1	[#]
Puffer-Übergabe-Zeit	1.5	[s]
Puffer-Position	0	[m]
Lift-Einlager-Punkt-Position	1	[ ]
Regal-Belegungsgrad	0.6	[%/100]
Regal-Belegungsmodus	Zufall	

Table 4-26: Rack parameters

vmax y-Rtg (Lift)	5	[m/s]
a+ y-Rtg (Lift)	7	[m/s^2]
a- y-Rtg (Lift)	7	[m/s^2]
Lift: Anzahl LAM	1	[#]
Lift-Totzeitanteil an Spielzeit (t0)	0.5	[s]
Lift-Spielzeit in z-Rtg (tz)	1.5	[s]
Lift Strategie	Ein- und Auslagern	
Anzahl Lift je Gasse	1	[#]

Table 4-27: Lift parameters

vmax x-Rtg (Shuttle)	2	[m/s]
a+ x-Rtg (Shuttle)	2	[m/s^2]
a- x-Rtg (Shuttle)	2	[m/s^2]
Shuttle-Totzeitanteil an Spielzeit (t0)	1	[s]
Shuttle-Spielzeit in z-Rtg (tz)	5	[s]
Shuttle: Spielzeit in z-Rtg (tz), 2.-4. Fach	1	[s]

Table 4-28: Shuttle parameters

In each scenario the system throughput is examined. Therefore the number of columns and the number of tiers for every simulation run is modified. Table 4-29 illustrates the parameter variation for the rack size. Thus 36 simulation runs within one scenario are executed, resulting in system throughput curves.

	Min	Max	Delta	
Anzahl simulierter Ein-Auslagerungen	50.000			[#]
Anzahl Ebenen	10	60	10	[#]
Anzahl Fächer pro Ebene	50	300	50	[#]

Table 4-29: Rack size variation

In the following section, scenario SC11 and scenario MC22 are exemplary examined.

4.7.1 Scenario SC11

In scenario SC11 the rack is single-deep and one lift with one load attachment devices is configured. The lift is executing the whole storage and retrieval orders. The system throughput curve for this scenario is shown in Figure 4-20.
With an increasing number of tiers also the throughput increases. Until the rack has 25 tiers the throughput decreases. The flow of the throughput curve is consistent.

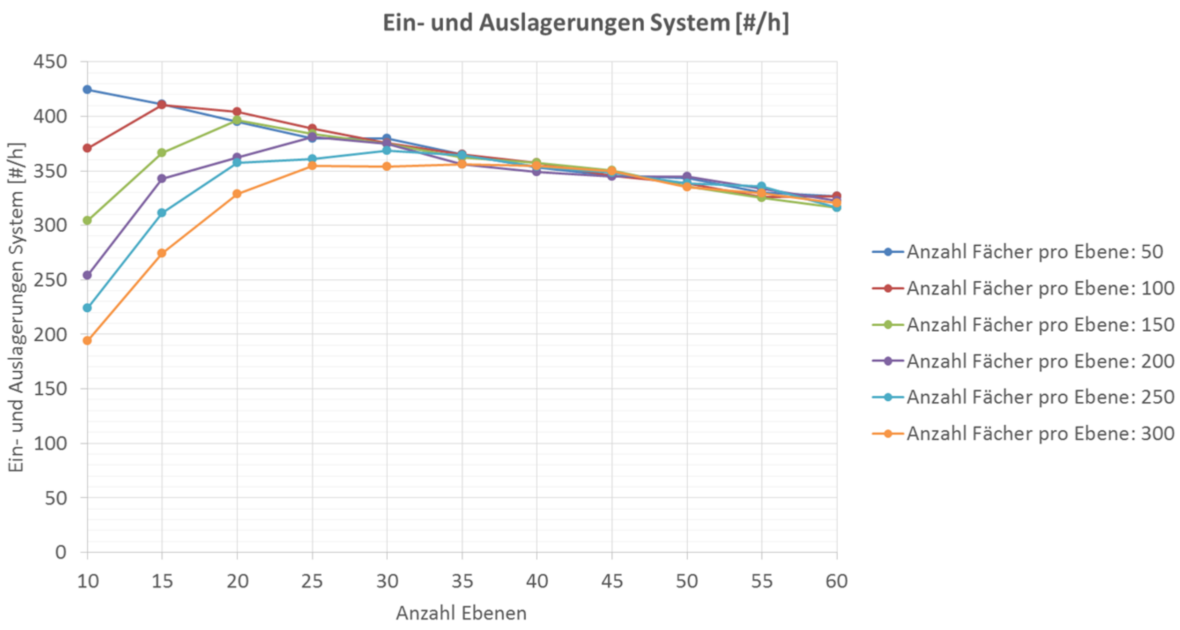

Figure 4-20: System throughput for scenario SC11

The convergence behaviour for scenario SC11 is displayed in Figure 4-21. The convergence behaviour is examined for a rack with 10 tiers and 100 columns.
It starts to converge by 70.000 storage and retrieval orders. After these 70.000 orders the confidence amplitude is smaller than one second which is the maximum permitted value for the confidence amplitude (Equation 3-4).

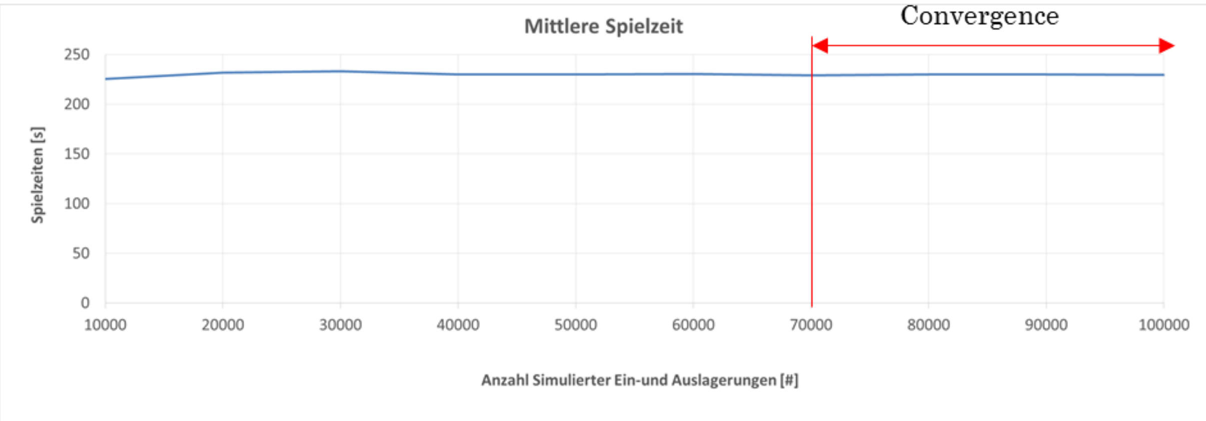

Figure 4-21: Scenario SC11 convergence behaviour

The curve for the system throughput (Figure 4-20) is consistent. Also the convergence behavior (Figure 4-21) is valid. Consequently the model is processing the scenario SC11 correctly.

4.7.2 Scenario MC22

In scenario MC22 the rack has a rack depth of four and two lifts with two load attachement devices. The kinematic parameters and the rack dimensions are the same as for scenario SC11. The system throughput depending on the number of tiers and the number of columns is displayed in Figure 4-22. The curves of the system throughput are consistent.

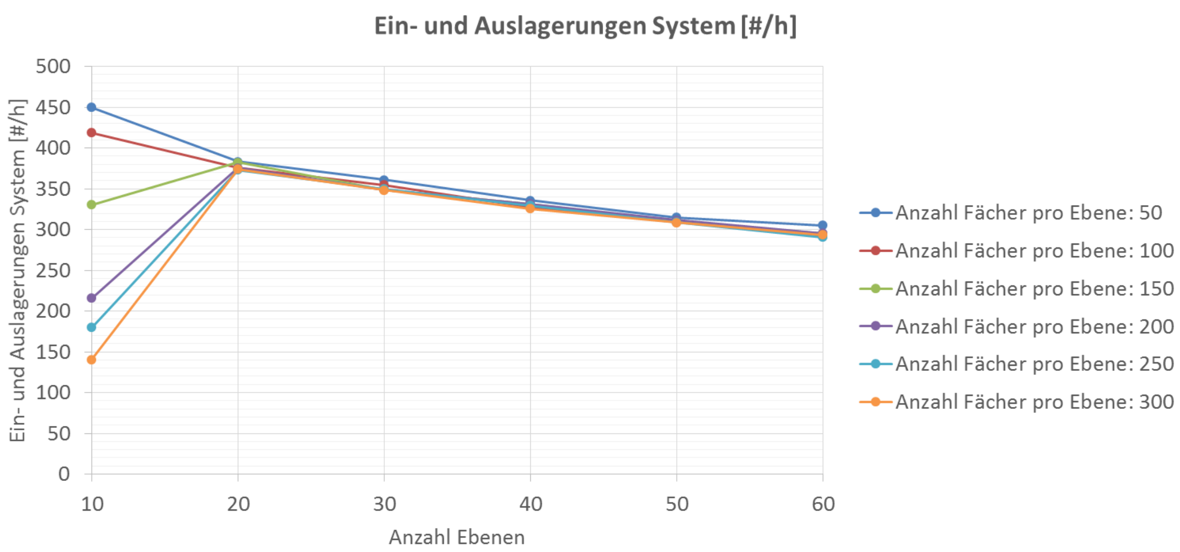

Figure 4-22: System throughput for scenario MC22

In Figure 4-23 the convergence behavior is displayed. In this scenario the model starts to converge at 80.000 storage and retrieval orders. In this case, for a rack depth of four, the permitted confidence amplitude is set to two seconds (Equation 3-4). This restriction is achieved after 80.000 orders. The model is processing the scenario MC22 correctly.

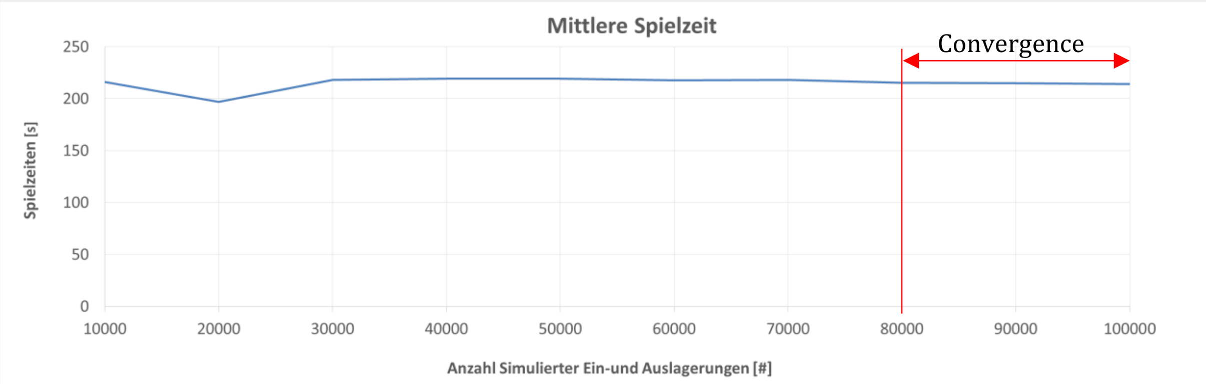

Figure 4-23: Scenario MC22 convergence behaviour

4.7.3 Comparison initial model – new model

For further investigations into the validity of the model, the system throughput of the actual model (v1.26.39) is compared with the system throughput of the initial model (v1.26.13) from the Institute of Logistics Engineering. The initial model already included the retrieval process but had only one rack site, therefore the actual model has been slightly modified in order to have also only one rack site.

For this comparison, 30.000 retrieval orders are carried out, while the buffer capacity is one and there is one lift per aisle with one load attachment device. Further input data is displayed in Table 4-30 to Table 4-32.

Regal	Min	Max	Delta	
Anzahl Ebenen	15	60	5	[#]
Anzahl Fächer pro Ebene	50	850	200	[#]
Regaltiefe (Z)	1			[#]
Breite Fach	550			[mm]
Höhe Fach	350			[mm]
Maximale Pufferkapazität	1			[#]
Puffer-Übergabe-Zeit	1.5			[s]
Puffer-Position	0			[m]
Lift-Einlager-Punkt-Position	0			[ ]
Regal-Belegungsgrad	0.7			[%/100]
Regal-Belegungsmodus	Zufall			

Table 4-30: Rack configuration for comparison of models

Shuttle		
vmax x-Rtg (Shuttle)	2.5	[m/s]
a+ x-Rtg (Shuttle)	1	[m/s^2]
a- x-Rtg (Shuttle)	1	[m/s^2]
Shuttle-Totzeitanteil an Spielzeit (t0)	1	[s]
Shuttle-Spielzeit in z-Rtg (tz)	3,5	[s]
Shuttle: Spielzeit in z-Rtg (tz), 2.-4. Fach	1	[s]

Table 4-31: Shuttle configuration for comparison of models

Lift		
vmax y-Rtg (Lift)	1	[m/s]
a+ y-Rtg (Lift)	1	[m/s^2]
a- y-Rtg (Lift)	1	[m/s^2]
Lift: Anzahl LAM	1	[#]
Lift-Totzeitanteil an Spielzeit (t0)	0.5	[s]
Lift-Spielzeit in z-Rtg (tz)	1.5	[s]
Lift Strategie	Ein- und Auslagern	
Anzahl Lift je Gasse	1	[#]

Table 4-32: Lift configuration for comparison of models

The system throughput of the initial model is displayed in Table 4-33 and in Table 4-34 the system throughput of the actual model is shown. These two tables are displaying the throughput depending on the number of tiers and the number of columns. Both models have the same results for the system throughput.

	Anzahl Ebenen	Anz_X =50[ ]	Anz_X =250[ ]	Anz_X =450[ ]	Anz_X =650[ ]	Anz_X =850[ ]
1	15	262	262	262	262	254
2	20	232	232	232	232	232
3	25	208	208	208	208	208
4	30	189	189	189	189	189
5	35	173	173	173	173	173
6	40	159	159	159	159	159
7	45	148	148	148	148	148
8	50	138	138	138	138	138
9	55	129	129	129	129	129
10	60	122	122	122	122	122

Table 4-33: Throughput values of model v1.26.13

	Anzahl Ebenen	Anzahl Fächer pro Ebene: 50	Anzahl Fächer pro Ebene: 250	Anzahl Fächer pro Ebene: 450	Anzahl Fächer pro Ebene: 650	Anzahl Fächer pro Ebene: 850
1	15	262	262	262	262	255
2	20	232	232	232	232	232
3	25	208	208	208	208	208
4	30	189	189	189	189	189
5	35	173	173	173	173	173
6	40	159	159	159	159	159
7	45	148	148	148	148	148
8	50	138	138	138	138	138
9	55	129	129	129	129	129
10	60	122	122	122	122	122

Table 4-34: Throughput values of model v1.26.39

The system throughput curve for the initial model is shown in Figure 4-24 and for the actual model in Figure 4-25. These curves are identical. The actual model delivers the same results as the initial model. Thus the actual model works as planned.

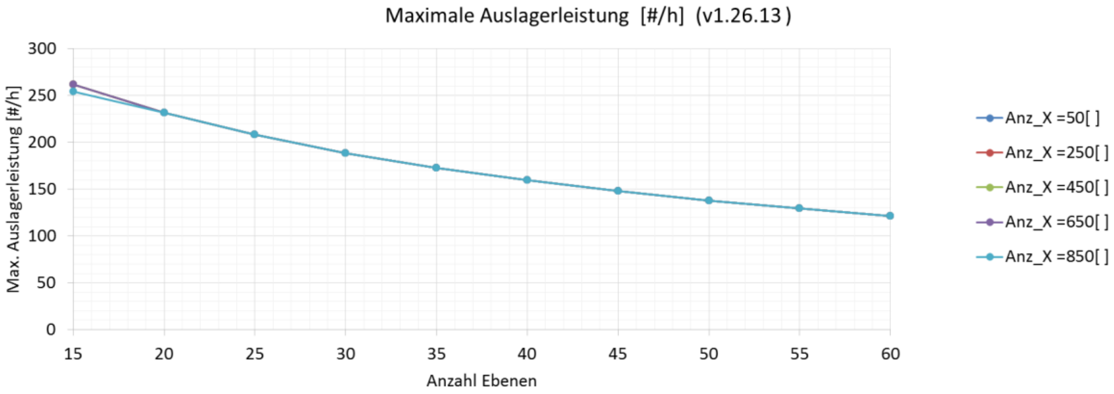

Figure 4-24: Throughput curve of model v1.26.13

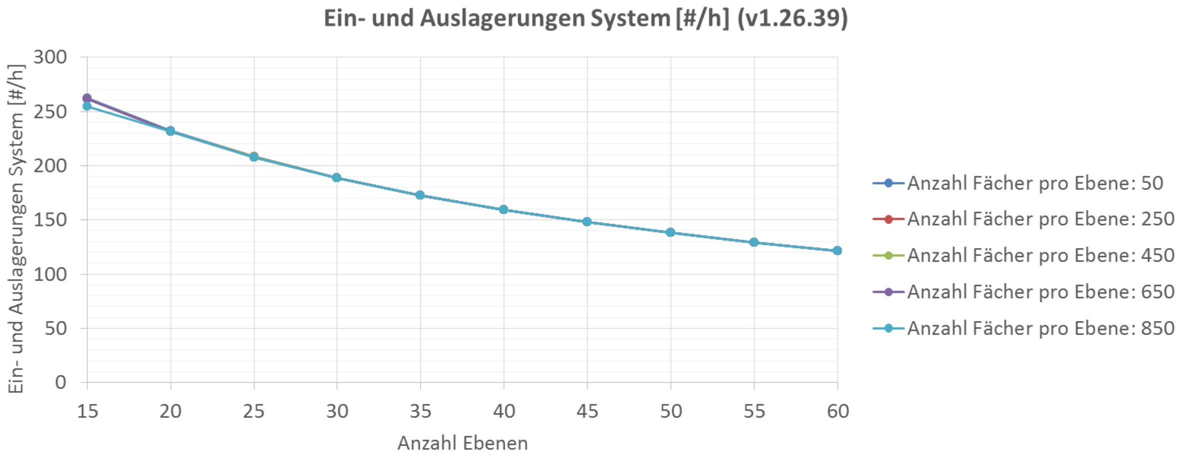

Figure 4-25: Throughput curve of model v1.26.39

5 Conclusion

The verification of the model and the functions revealed that the basic system is processing correct. The handling of the boxes and single events during a simulation run are executed as required. There are only a few functions which are not processing as planned. The random order creation is not uniform distributed over the rack and also for the function ‘order sequencing’ the batch size creation does not work as required. Therefore further investigations in these functions have to be made and the model has to be revised.

The executed scenarios have shown that the model is convergent for these given specifications. For a rack with one or two lifts, a rack depth of one or four and with a combined process of storing and retrieving of the boxes the model will converge. Also for the basic case of a rack with one lift and the boxes are only stored or retrieved, the model will always converge. The executed scenarios have revealed, that the model is processing as required.

The results for the system throughput seem to be applicable and they also correspond to the initial tool. However, the results of the system throughput should be compared with the system throughput of a real system in order to verify the validity of the model.

With the function of the ‘parameter variation’ characteristic curves of the system throughput and the lift/shuttle utilization can be created. With this curves conclusions on the system can be drawn.

The model should be extended with regard to the number of aisle in the system. It should be possible to simulate more aisles at the same time. These aisles are then connected by picking stations. With an increasing number of aisles in the system also the number of processing steps for the model is increasing. To ensure a good simulation performance the model should then be implemented in a more powerful programming language compared to Visual Basic for Applications.

6 Lists

6.1 List of figures

6.2 List of tables

6.3 List of equations

6.4 List of references

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7 Appendix

Tool: Shuttle Analysis – Manual

Table of Contents

7.1 Interface

The Tool „Shuttle analysis” consists of several spreadsheets (Table 7-1).

Spreadsheet name	Content	
Übersicht	Button to run the simulation	
Variablen	Short description about the main variables in the code	
I1_	Main input mask	Enter data
I2_	Input mask for the order list and rack occupation	Optional
O1_	Output table for system throughput	
O2_	Output table for the lift utilization	Always output
O3_	Output table for the shuttle utilization	
O4_	Output table for additional statistics	
E1_	Evaluation of the order list and rack occupation	
E2_	Evaluation of the fulfilled orders	
E3_	Evaluation of the event list	
E4_	Evaluation of the ABC-distribution	Optional output
E5_	Evaluation of the order sequencing	
E6_	Evaluation of model convergence	
E7_	Evaluation of random numbers	
E8_	Tracking of specific boxes	
E9_	Quality of the rack occupation	
E10_	Quality of the order creation	

Table 7-1: Spreadsheets in the tool

Input mask

The spreadsheet "I1_" represents the main input mask for the tool. Yellow highlighted cells are input cells (Table 7-2).

Parameters | Input values | Units of the parameters

Input Maske	Min	Max	Delta	
Anzahl simulierter Ein-Auslagerungen	10 000	30 000	100	
Regal				
Anzahl Stellplätze	10 000	40 000	30 000	[#]
Anzahl Ebenen	10	10	0	[#]
Anzahl Fächer pro Ebene	100	100	0	[#]
Regaltiefe (Z)	1	1	1	[#]
Breite Fach	1000	850	300	[mm]
Höhe Fach	1000	950	600	[mm]
Länge (x)	100			[m]
Höhe (y)	10			[m]
Maximale Pufferkapazität	2	4	3	[#]
Puffer-Übergabe-Zeit	1.5			[s]
Puffer-Position	0			[m]
Lift-Einlager-Punkt-Position	0	5	5	[ ]
Regal-Belegungsgrad	0.6	0.6	0	[%/100]
Regal-Belegungsmodus	Zufall			
Lift				
vmax y-Rtg (Lift)	5			[m/s]
a+ y-Rtg (Lift)	7			[m/s^2]
a- y-Rtg (Lift)	7			[m/s^2]
Lift: Anzahl LAM	1	2	1	[#]
Lift-Totzeitanteil an Spielzeit (t0)	0.5			[s]
Lift-Spielzeit in z-Rtg (tz)	1.5			[s]
Lift Strategie	Ein- und Auslagern			
Anzahl Lift je Gasse	1	1	0	[#]
Shuttle				
vmax x-Rtg (Shuttle)	2			[m/s]
a+ x-Rtg (Shuttle)	2	2.2	0.2	[m/s^2]
a- x-Rtg (Shuttle)	2			[m/s^2]
Shuttle-Totzeitanteil an Spielzeit (t0)	1			[s]
Shuttle-Spielzeit in z-Rtg (tz)	5			[s]
Shuttle: Spielzeit in z-Rtg (tz), 2.-4. Fach	2	4	2	[s]

Table 7-2: Excerpt from the input mask

7.2 Parameter variation

Select the parameter variation by using the drop down button on spreadsheet “I1_” (Table 7-3).Define for each parameter a minimum value (1), a maximum value (2) and an increment value (3) (Table 7-4).

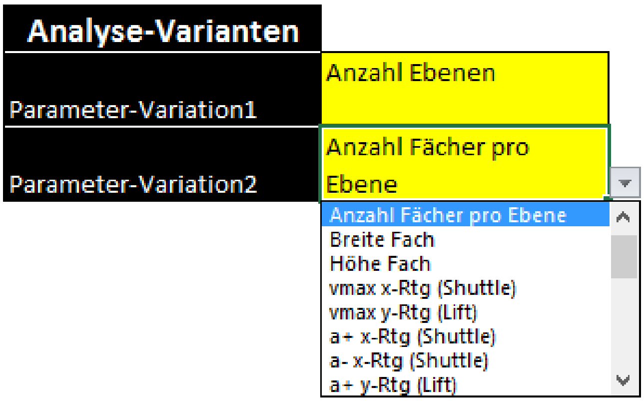

Table 7-3: Input mask for the parameter variation

	(1) Min	(2) Max	(3) Delta	
Anzahl Ebenen	5	40	5	[ ]
Anzahl Fächer pro Ebene	100	500	100	[ ]

Table 7-4: Exemplary values for the parameter variation

7.3 Storage sequence

With this strategy the user defines the simulation sequence. That means it defines the course of handling the boxes. Three different strategies can be set (Table 7-5). First, during the simulation boxes are only retrieved from the rack (1). Second, boxes are only stored into the rack (2) and third is a combination of storing and retrieval (3).

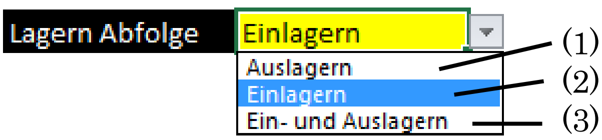

Table 7-5: Input mask for the storage sequence

Table 7-6 shows the input mask for the degree of filling. Either “constant” (1) or “variable” (2) can be selected. It is important to mention that when as a storage sequence “storing” or “retrieval” is selected, that the degree of filling has to set to “constant”. This has to be considered, otherwise an error occurs. The reason for this is the internal data processing of the tool.

Table 7-6: Input mask for degree of filling

7.4 Rack occupancy strategies

The first possible occupancy strategy is to randomly occupy the rack (1), the second is also to randomly occupy the rack but avoid empty bays between occupied bays (2). The third strategy is to occupy the rack by a predefined occupation list (3) and the fourth strategy is to occupy the rack during the simulation in a certain way (4) (Table 7-7).

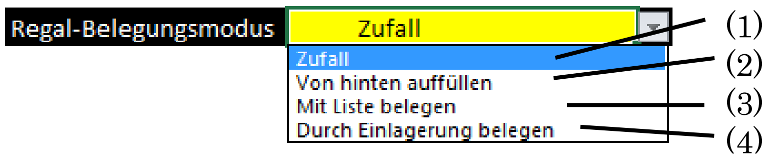

Table 7-7: Input mask for the rack occupancy strategies

7.4.1 Occupy with occupation list (Mit Liste belegen)

In this mode, the user has to define in advance where which box is located in the rack. Therefore an occupation list has to be created. In this list the user insert the box name (1), the tier position (2), the column position (3) and the depth where the box shall be located (4) (Table 7-8). When running the simulation, the rack is occupied according to this predefined occupation list. The occupation list is located on the spreadsheet “I2_”. The list has a predefined format; the user only has to insert the values.

	Regal belegen			
	(1)	(2)	(3)	(4)
	Box Nr.	Ebene	Fach	Tiefe
1	Box1	1	1	4
2	Box2476	1	1	6
3	Box2413	1	1	7
4	Box2309	1	1	8
5	Box61	1	2	3
6	Box2	1	2	4
7	Box2477	1	2	5
8	Box2414	1	2	6
9	Box2367	1	2	7
10	Box2310	1	2	8

Table 7-8: Excerpt from the occupation list

7.4.2 Occupy through storage process (Durch Einlagerung belegen)

In this mode the rack is by default empty. During the simulation the boxes are stored into the rack and thus the rack will be filled. Some crucial settings have to be set on spreadsheet "I1_". First the degree of filling has to be set to "constant" (1). Second the storage sequence has to be set to "store" (2) and third the task has to be set to "order list" (3) (Table 7-9).

Simulation Ablauf		
Füllgrad	konstant	(1)
Lagern Abfolge	Einlagern	(2)
Auftrag	Auftragsliste	(3)

Table 7-9: Important settings for the "occupy through storage process"

The third setting has to be made that the simulation knows with which boxes the rack has to be occupied. Here an order list has to be created in advance. The order list is located on the spreadsheet "I2_". In this order list a unique box name has to be set (1), the tier to store the box (2), the column (3), the depth (4) and the action (storing) for the box (5) (Table 7-10).

Auftragsliste					
	(1)	(2)	(3)	(4)	(5)
	Box Nr.	Ebene	Fach	Tiefe	Aktion [Einlagern/Auslagern]
1	Box1	1	1	4	Einlagern
2	Box2476	1	1	6	Einlagern
3	Box2413	1	1	7	Einlagern
4	Box2309	1	1	8	Einlagern
5	Box61	1	2	3	Einlagern
7	Box2477	1	2	5	Einlagern
8	Box2414	1	2	6	Einlagern
9	Box2367	1	2	7	Einlagern
10	Box2310	1	2	8	Einlagern

Table 7-10: Excerpt from the order list

7.5 Order list

Define which orders have to be fulfilled during the simulation. Therefore an order list has to be created in advance. In this list, a unique box name has to be set (1), the tier to store the box (2), the column (3) the depth (4) and the action (storing / retrieving) for the box (5) (Table 7-10). When the order list is selected, some settings have to be done in advance:

The rack occupation has to be set to "occupy with occupation list" and also the occupation list has to be defined. The orders for the order list have to be created out of the occupation list, to ensure that the boxes really exist (Table 7-11).

Regal-Belegungsmodus	Mit Liste belegen	[ ]

Table 7-11: Rack occupation

The degree of filling has to be set to "constant" (1), the storage sequence has to be set to "storing and retrieval" (2), and the tasks have to be set to "order list" (3) (Table 7-12**Error! Reference source not found.**).

Simulation Ablauf		
Füllgrad	konstant	(1)
Lagern Abfolge	Ein- und Auslagern	(2)
Auftrag	Auftragsliste	(3)

Table 7-12: Input mask for the order list

7.6 Order sequencing

Before running the orders batch wise, some settings have to be done.
The task has to be set to "sequencing" (Table 7-13).

Auftrag	Sequenzierung

Table 7-13: Task execution: Sequencing

The batch size has to be defined. The batch size can be uniformly distributed (1), normal distributed (2) or of constant size (3) (Table 7-14).

Table 7-14: Input mask for order sequencing

When selected uniform distributed, the user has to define the minimum and maximum value. For normal distributed, the mean value and the standard deviation have to be inserted and for a constant batch size, the constant number of boxes in the batch has to be specified (Table 7-15).

Auftrag	Sequenzierung	(1)
Losgröße	Gleichverteilt	(2)
Min Wert	2	(3)
Max Wert	6	(4)

Table 7-15: Input mask for uniformly distributed batch

7.7 Evaluation functions

During the simulation a plenty of information is generated. This includes information about the time when which box is manipulated and the location, waiting times, cycle times, ABC distribution, etc. To make the whole simulation run more transparent all this information can be displayed on different spreadsheets. For each kind of additional information, a function exists to display this information.

7.7.1 Display occupied rack

How the tool has occupied then rack can be seen on spreadsheet "E1_". With the setting "display occupied rack", the boxes in the rack and their location are displayed in a table (Table 7-16).

Regalbelegung ausgeben	Ein	Tabellenblatt "E1_"

Table 7-16: Input mask to display the occupied rack

7.7.2 Display fulfilled order list

To display the fulfilled order list, the function “verify order list” and “additional analysis have to be set to on (Ein) (Table 7-17). The fulfilled order list is then displayed on spreadsheet “E1_”.

Überprüfen			
Regalbelegung ausgeben	Aus	Tabellenblatt "E1_"	
Auftragsliste überprüfen	Ein	Tabellenblatt "O4_"	(1)
Zusätzliche Auswertung	Ein	Tabellenblatt "E1_"	(2)
"Echte" Zufallszahlen	Ein		
Abgearbeitete Aufträge ausgeben	Aus	Tabellenblatt "E2_"	
Ereignisliste ausgeben	Aus	Tabellenblatt "E3_"	

Table 7-17: Display fulfilled order list

7.7.3 Display fulfilled random orders

All the single orders during a simulation can be stored and detail information of the orders can be displayed. The fulfilled orders are then displayed on spreadsheet “E2_”. For this, in the input mask on spreadsheet “I1_” the function “additional analysis (1) and “display fulfilled tasks” (2) have to be set to on (Ein) (Table 7-18).

Überprüfen			
Regalbelegung ausgeben	Aus	Tabellenblatt "E1_"	
Auftragsliste überprüfen	Aus	Tabellenblatt "O4_"	
Zusätzliche Auswertung	Ein	Tabellenblatt "E1_"	(1)
"Echte" Zufallszahlen	Ein		
Abgearbeitete Aufträge ausgeben	Ein	Tabellenblatt "E2_"	(2)
Ereignisliste ausgeben	Aus	Tabellenblatt "E3_"	

Table 7-18: Display fulfilled random orders

7.7.4 Display ABC- distribution

The rack can be occupied by three different ABC-distributions and the segmentation of the rack can be displayed on spreadsheet “E4_” (Table 7-19).

ABC-Verteilung ausgeben	Ein	Tabellenblatt "E4_"

Table 7-19: Input mask to display the ABC-distribution

In the input mask on spreadsheet “I1_”, the ABC-strategy has to be selected (1), the order proportion on the ABC goods (2) and the storage proportion on the ABC-goods (3) have to be specified (Table 7-20).

Lager-Strategie			
ABC-Verteilung	Block		(1)
Auftragspositionen-A-Anteil	0,8	[%/100]	(2)
Auftragspositionen-B-Anteil	0,15	[%/100]	
Auftragspositionen-C-Anteil	0,05	[%/100]	
Lagerpositionen A-Anteil	0,2	[%/100]	(3)
Lagerpositionen B-Anteil	0,3	[%/100]	
Lagerpositionen C-Anteil	0,5	[%/100]	

Table 7-20: Input mask for the ABC-distribution

7.7.5 Display event list

All the single actions which are happening during the simulation can be displayed. These actions are sorted in ascending order and displayed on spreadsheet "E3_".
Define the range of the event list. Either set the upper and lower border of the event number or the upper and lower border of the time (1).
Set "Eriegnisliste visualisieren" on "Ein" in order to visualize the event list (2) (Table 7-21).

Ereignisliste ausgeben	Ein	Tabellenblatt "E3_"	
Ergebnisliste Bereich	Anzahl Ereignisse		(1)
Min	1	[#]	
Max	200	[#]	
Modus	gesamtes System		
Ereignisliste visualisieren	Aus	(2)	

Table 7-21: Input mask for the event list

Also the tracking modus can be chosen. The whole system, a specific shuttle, a specific lift or a specific box can be tracked.

7.7.6 Display batch size

Display the batches on spreadsheet "E5_"(Table 7-22).

Sequenzierung ausgeben	Ein	Tabellenblatt "E5_"

Table 7-22: Display batch size

7.7.7 Additional statistics

Additional information about the simulation run is displayed. These additional statistics are shown on spreadsheet "O4_" and the operating points can be compared.

Zusätzliche Auswertung	Ein	Tabellenblatt "O4_"

Table 7-23: Display additional statistics

7.7.8 Examine convergence

To display to convergence behavior of the model, set the parameter variation 1 to "Anzahl simulierter Ein-Auslagerungen" (Table 7-24).

Analyse-Varianten	
Parameter-Variation1	Anzahl simulierter Ein-Auslagerungen

Table 7-24: Excerpt of the parameter variation

Insert the amount of storage and retrieval actions per simulation run (Table 7-25).

	Min	Max	Delta
Anzahl simulierter Ein-Auslagerungen	10 000	30 000	100

Table 7-25: Input mask for the amount of simulation runs

Set the additional statistics to "Ein"(Table 7-26).

Zusätzliche Auswertung	Ein	Tabellenblatt "O4_"

Table 7-26: Input mask for addition statistics

And set show convergence to "Ein" (Table 7-27).

Konvergenz zeigen	Ein	Tabellenblatt "E6_"

Table 7-27: Input mask to show convergence

The convergence behavior will then be displayed on spreadsheet "E6_".

7.7.9 Display random numbers

In order to examine the random number function, the function can be tested and the created random numbers can be displayed on spreadsheet "E7_".

Zufallszahlen ausgeben	Ein	Tabellenblatt "E7_"

Table 7-28: Input mask to display random numbers

7.7.10 Display the quality of rack occupation

Examine the quality of the rack occupancy. The occupation is displayed on spreadsheet “E9_”.

Verteilung Regalbelegung ausgeben	Ein	Tabellenblatt "E9_"

Table 7-29: Input mask to display the quality of the rack occupation

7.7.11 Display the quality of order creation

The orders during the simulation are created randomly. Therefore also the Excel VBA random number function is used. The quality of the order creation can be examined.

Verteilung der Aufträge ausgeben	Ein	Tabellenblatt "E10_"

Table 7-30: Input mask to display the quality of order creation