Author: BSc. Mairamhof Matthias

Spatial Motion Behaviour of Parcels in Singulation Processes: A DEM – Simulation Approach

MASTER'S THESIS

to achieve the university degree of

Diplomingenieur (Dipl.-Ing.)

submitted to

Institute of Logistics Engineering (ITL)

Supervisor: Dipl.-Ing. Matthias Fritz

October, 2015

EIDESSTATTLICHE ERKLÄRUNG

AFFIDAVIT

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt, und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht habe. Das in TUGRAZonline hochgeladene Textdokument ist mit der vorliegenden Masterarbeit/Diplomarbeit/Dissertation identisch.

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master's thesis/diploma thesis/doctoral dissertation.

07. 10. 2015

Datum / Date

Rainramhof Matthias

Unterschrift / Signature

Table of Contents

1 Introduction

The emergence of Internet-Commerce has completely changed the nature of traditional delivering [BIE15]. Due to the increasing importance of the CEP-services (Courier, Express and Parcel), the method of sorting parcel becomes more important for the feasibility of a stable supply chain in this logistic branch. The global CEP-market is growing, e.g., in 2014 there were in Germany 4.5% more express consignments (four out of five shipments are parcels) and the revenue increased by 3.6% compared with the previous year [BIE15].

1.1   Consideration of the Research Field

The task of this master thesis is an experimental investigation of the motion behaviour of parcels during the singulation procedure. A parcel passes generally through five steps in a distribution centres [JtH05]:

1. Feeding area
2. Preparation area
3. Identification
4. Sortation system
5. Discharging area

Especially the first two steps of this process chain represent possible bottlenecks because the relatively slow manual unloading of a transport vehicle (e.g. container) including the single sortation of the parcels beats the cost-intensive automation of the further process steps [FWJ13]. Figure 1 exhibits all five functional parts of a distribution centre [FWL+15]. Singulation occurs mainly in the first two areas, which contain the unloading of containers and the preparation of parcels for identification.
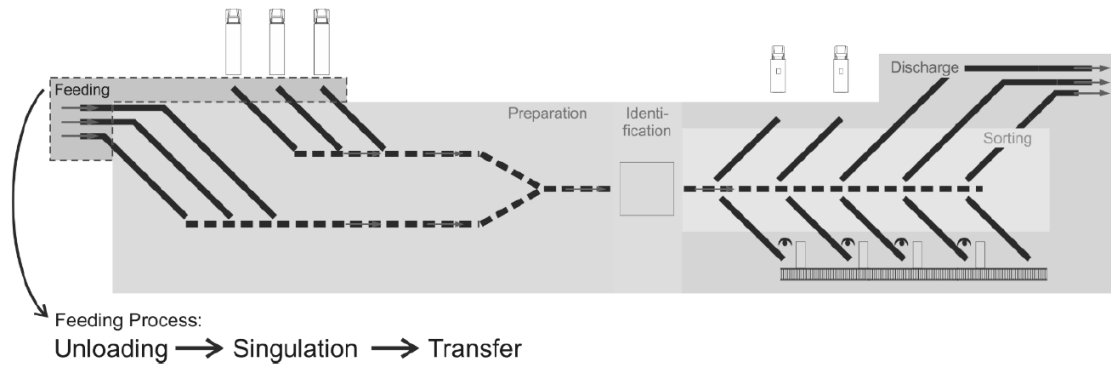
Figure 1: Processes in distribution centres [FWL+15]

Possible approaches for mechanical parcel singulation represent dynamic forces like drops, tosses, or kicks. These singulation methods are basically generated by mechanical working principles like velocity changes or level differences whereby a bulk of parcels falls from an upper conveyor belt via a fall height on a lower positioned conveyor belt. For avoiding unnecessary expenses in the development process of conveying equipment ([HÄF98], [FWL+15]), it requires the application of an appropriate simulation tool for the examination of new singulation approaches that meet the objective of increasing throughputs in distribution centres. DEM-based simulation tools meet many requirements for the implementation of such singulation mechanisms. If a large volume of parcels is jammed and dammed into a bulk on a conveyor belt, there act a lot of contact forces between the working surfaces of parcels ([CRR+14]; [FWJ13]). Therefore, it is essential to build a real test scenario for measuring experimental data that helps to validate and verify the quality of the implemented simulation model. The collected data helps to describe the motion behaviour of parcels during singulation procedure.

For the evaluation of a simulation model, it requires the definition of a convenient quality characteristic that analyses the whole mechanism regarding its main influencing factors (e.g. damping, friction, etc.). The statistical tool Design of Experiments (DoE) provides for the influencing factors appropriate evaluation criteria and a set of quantitative and qualitative indicators that help achieving quality objectives. With this kind of sensitivity analysis it is possible to set the value ranges for each influencing factor in the simulation in a proper manner that the deviations between outputs from simulation and experimental tested

measures fit together. The successful implementation of an applicable singulation model should prove, if parcel movements during the singulation procedure can be mapped by the help of simulation. In order to take full advantage of this simulation based approach, it should be possible to meet the increasing requirements in the parcel industry and to satisfy the rising consumer demand.

The requirements of faster delivery times or increased volume handling regarding seasonal peaks, all impact the material flow layout in parcel-and postal-facilities [BIE15]. Parcel singulation into a single-filed flow with defined gaps in between is an important process within material handling systems and it is crucial in throughput optimization [INT15]. Current systems contain large systems of roller or belt conveyors, deflecting elements, chutes and recirculation lines, all of them reduce valuable floor space, increase noise and require high work input [SIE09]. That causes big effort and leads to an enormous potential for development regarding cost effectiveness and work simplification [SIE13].

Today modern and big CEP-services do still use not or partly automated sortation systems because of the high investment costs by a coinstantaneous low degree of utilisation. To fit a small time slot even in high load periods, it is necessary to install sortation systems with a high sortation rate. This high efficiency of the sortation device is needed a few hours a day, the remaining time the sortation system is working in partial load or shut down of production [JtH05].

Dirk Jodin and Michael ten Hompel compiled in Figure 2 the most important breakthroughs in sorting technology from manual sorting up to automatized singulation of nearly 30,000 piece goods per hour [JtH05].
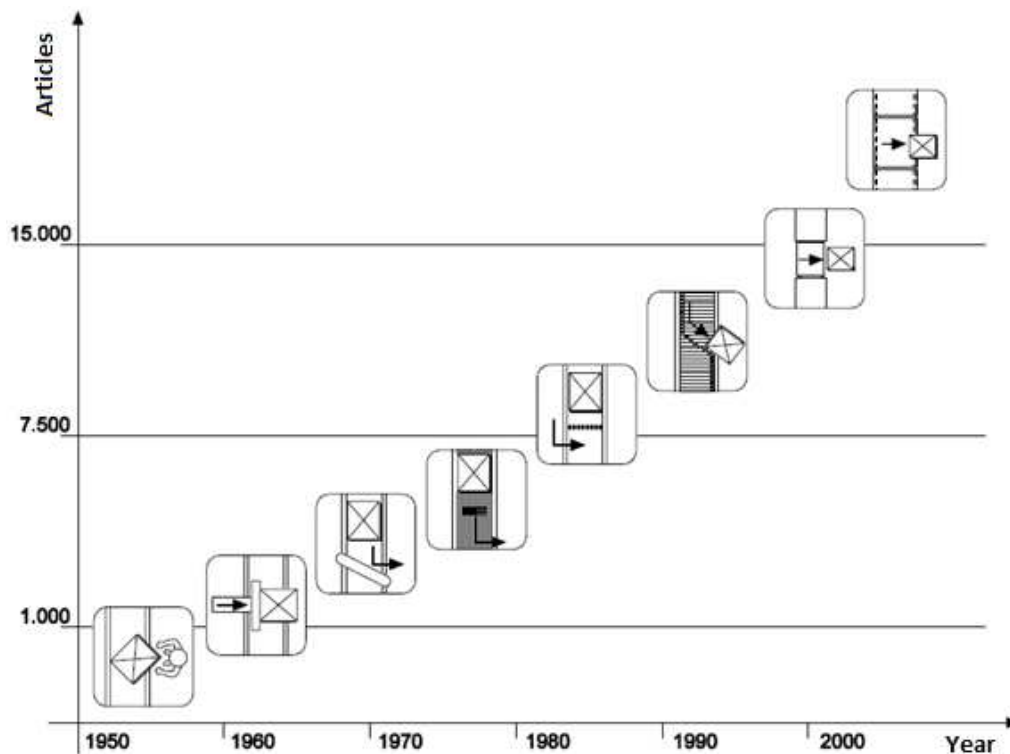
Figure 2: Development of sortation capacity [JtH05]

The criteria of demarcation for Courier-, Express- and Parcel-services (CEP) include the weight and volume of shipments, the pace of the goods traffic and the offered services. The following three sub-points give a closer look in the spheres of activities from the different services.

Courier

A courier service (also called courier or messenger) transports the shipment personally and directly from sender to recipient. The crucial features to distinguish this type of service with respect to the express and parcel services are the permanent monitoring of the postal item and the individual transport design, which ensures a special safety in the transport chain. Apart from a variety of individual entrepreneurs, it is necessary to involve switching centres in this segment. They have the task to transfer the shipments to affiliates. Personally escorted transport can be found both in the national well as international traffic. For example, the German Railways offers a courier service whereby a train guard accepts, supervises and hands over a courier delivery [JtH05].

Express

In contrast to courier services, express consignments are transported via a sortation centre to the receiver. Regarding collective transports, an essential feature of express services is the accelerated transport with binding delivery times. Express shipments differ from freight forwarding services by promised short source-target duration. The large express delivers companies are just as highly automated as parcel services, but they transport also larger piece goods up to full loads, typical express services in Germany are "Overnight-" and "In-night- transports" [JtH05]. Vanderlande Industries classified in Table 1 their express distribution centres by the material flow in the network nodes [VAN15].

Table 1: Classification of express distribution centres by Vanderlande [VAN15]

Abbreviation	Quantity	Unit
S	<2,500	[express consignments/hour]
M	2,500-8,000	
L	8,000-14,000	
XL	14,000-30,000	[#/h]
XXL	>30,000	

Parcel

Parcel services are system relevant service providers that work with a high level of standardization. Regarding to predefine operation steps the parcel cycle from sender to recipient takes usually a little bit longer than for express services and the transported parcels are restricted according size (1.75m) and weight (31.5kg). The cycle time can often derived from national road and rail traffic that means the recipient receives the parcel predominantly on the following working day, The typical sequence and material flow for this industry can be shown in Figure 3 with the example of the company "Deutsche Paket Dienst" (DPD) [JtH05].

The parcels will be picked up usually between 12 a.m. and 5 p.m. at the customer, than follows the sortation process (2 p.m.-8 a.m.) in the dispatch depots. The majority (70%) of the parcels are sent directly to the recipient depots and 30%

are sorted again (8 p.m.-6 a.m.) in so called HUB (German: Hauptumschlagsbasis~ cargo hub). Afterwards (5 a.m.- 8 a.m.) follows the distribution of the parcels to the respective delivery routes. The parcels arrive at the recipient usually between 8 a.m. and 3 a.m. [JtH05].
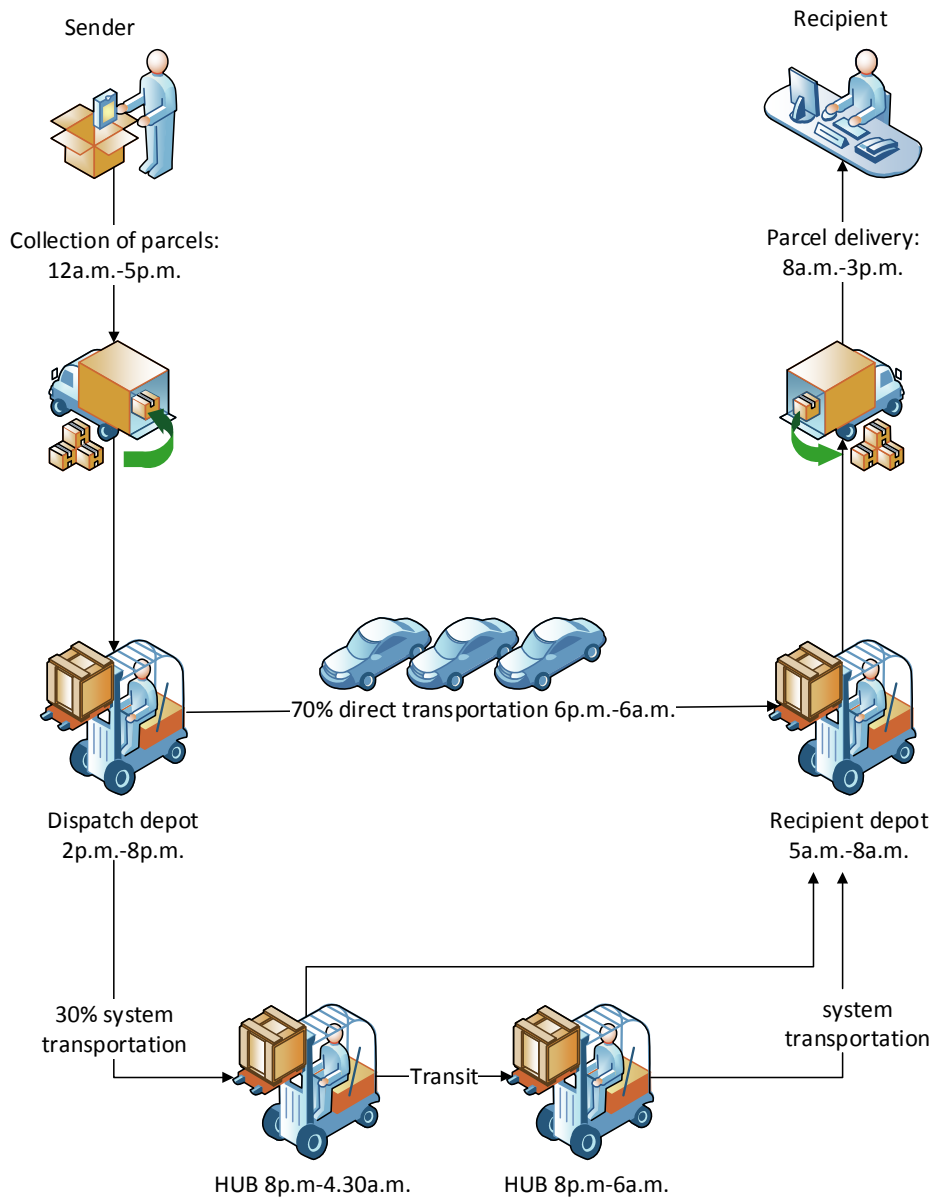
Figure 3: Exemplary operation of a parcel service [JtH05]

The sortation capacity depends on the time frame, the required performance of 3,000- 7,000 parcels per hour for a dispatch depot is quite low. In a HUB- and recipient depot the capacity raises up to 16,000 parcels per hour [JtH05].

1.2   Simulation in the Product Development Process

Compared to conventional test stands, simulation offers significantly advantages regarding cost effectiveness and reproduction of real physical behaviour in the development process of conveying equipment [FWL+15]. The objective of a cost effective parcel fulfilment and delivery by simplification the existing high-tech singulation approaches needs the use of simulation in the product development process ([SIE13]; [HÄF98]). Simulation reduces large numbers of iteration loops and expensive prototypes in early stages of the product development process [HÄF98]. The feasibility of simulation depends on the knowledge about system structure, parameters, input variables and a proper simulation environment of a product as a complete system or an assembly [HÄF98]. The cost savings should primarily take place through minimized space requirements, continuous flow of parcels, easy maintenance and an optional processing during identification (scanning, volume measurement, weighing) ([SIE13]; [BEU14]). A parcel singulation system should be able to transform a random input of parcels from a collector belt (multiple merging lines) into a *"streamlined flow in which each parcel is uniformly separated, spaced and aligned"* [BEU14]. The efficiency of the system ensures a steady parcel flow with appropriate orientation, seriously reduced recirculation rates, missorts, or parcel jamming due to side-by-sides arrangements, as well as the required labour input for resolving such problems. The singulation scenario "waterfall" is described, using Design of Experiments (DoE), with a measurable quality characteristic "position offset" (see 3.3). This model is tested on its main influencing factors and the interactions between these parameters. Therefore, the experiments must be implemented in a proper simulation tool and the outputs will be checked via comparison of measurements of a real physical model (see chapter 3.1 and 3.2).

1.3 Task

A parcel singulator transforms a bulk of parcels into a single-filed parcel flow in which each parcel is "uniformly separated, spaced and aligned" [BEU14]. Therefore, the logistic industry is conducting surveys that investigate the feasibility of certain singulation approaches with the major goal of achieving valid results of all research. These results should contain an accurate positioning of parcels in a significantly smaller footprint than alternative alignment options [SIE13]. This master thesis handles basically with the 3D-singulation approach (waterfall scenario in chapter 3.1) and deals with the following key question:

- Is it possible to reproduce the spatial motion behaviour of one or more parcels during singulation procedure from 3D to 2D via simulation?

For conducting this research question, following three aspects must be considered:

1. Determination of the infeed area: How does the cargo bulk (parcel pile) come to the conveyor belt? Definition of a real scenario for the parcel pile. Singulators have to deal with a large numbers and volumes of parcels; therefore, it is crucial to define an appropriate experimental setup like emptying a parcel container on a conveyor belt or the specification of a particular parcel arrangement like a parcel tower whereby several parcels lie on top of each other and imitate a bulk scenario.

2. Determination of the quality of the singulation-degree, if the bulk is transformed in a continued parcel flow with defined gaps. The main focus is to elaborate different characteristic lines which specify a singulation mechanism like a deflector- or the waterfall-principle. These characteristic lines should help the end user choosing the right singulator for a certain parcel-heap.

3. Determination of design parameters regarding user case. Investigation of the singulation procedure by simulation and determination of the main influencing parameters during the separation process by the help of experimental design approaches. It should be found a proper parameter set for reasoning the simulation approach and for constituting further research activities on this field.

1.4 Structure of the Master Thesis

This chapter has so far dealt with the surroundings of the singulation procedure and described closer the environment like e-commerce and distribution centres. Furthermore, the authorization of the simulation approach in the development process has been considered and the task was defined.

In the next chapter 2 follows a general problem analysis and the current state of the art will be discussed. This chapter analyses the current state of the literature and describes the singulation procedure with some existing solutions from industry.

Chapter 3 deals with the investigation of the waterfall scenario and explains own approaches, hypotheses and theories. This section gives a closer look on the simulation tool PFC3D and the analysing tools like DoE and neural networks.

Chapter 4 lists the measurements from real waterfall investigation and contains the measurements from DoE analysis and the neural network approach.

Chapter 5 includes the validation and verification of theories from chapter 3 with the results and means of chapter 4.

Chapter 6 summarizes the most important findings and gives an outlook on possible further research activities.

Chapter 7 registers the different lists and chapter 8 displays the program code and the achieved results in tabular form.

2 Problem Analysis and Background

This master thesis intends the experimental investigation of a singulation method that transforms a parcel bulk into a controlled stream of parcels with defined gaps in between. Figure 4 gives a rough overview of a typical cargo conveyor. The parcels come with a random orientation and arrangement from several charging lines (input, sources) on a conveyor belt and will be united there (merging). Afterwards, the parcels must be singulated before the parcels can be discharged over several output lines (branching) [AIK04].
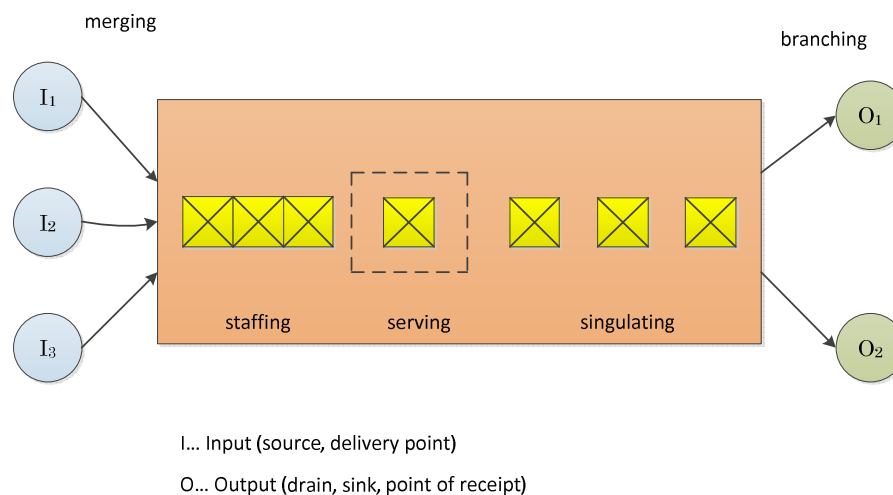
Figure 4: Schematic diagram of a cargo conveyor [AIK04]

This chapter gives an introduction in the topic of sortation and singulation procedures. This chapter is based on the funnel principle, where is processed from the whole sortation system to the singulation operation.
The first subchapter gives a closer look on the five functional parts of a distribution centre that were briefly mentioned in chapter 1.1.
The second subchapter depicts the four general selection criteria for sortation systems, whereby the cargo specific criteria manipulate the highest impact on the singuation approach.

In subchapter three, a screening through the state of the art highlights examples of sortation approaches and the current handling of singulation operations within those systems.

In the final point of this chapter displays a specific classification of singulation methods due to the predominant effect of their working principles and the singulation dimension (3D to 2D, 2D to 1D and 3D to 1D).

2.1 Structure of Sortation Systems

The structure of a sortation system contains roughly four different components. It consists additionally of the non-technical system components operation strategy, process organization and plant control [JtH05].

The components with their subtasks are illustrated in Figure 5. The different operating steps of piece good are settled in funnel shape from sortation system to distribution conveyor.
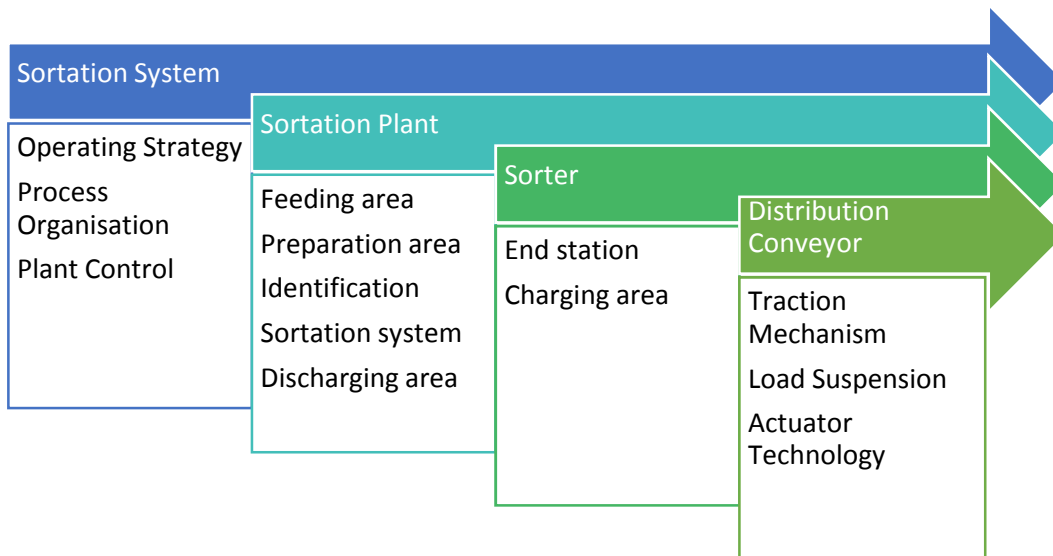
Figure 5: Structure of a sortation system [JtH05]

The sortation plant consists of several paired or parallel sorters and includes conveying in functional areas of feeding, preparation, identification, sortation and discharging. Figure 6 depicts the structure of a sortation plant [JtH05].
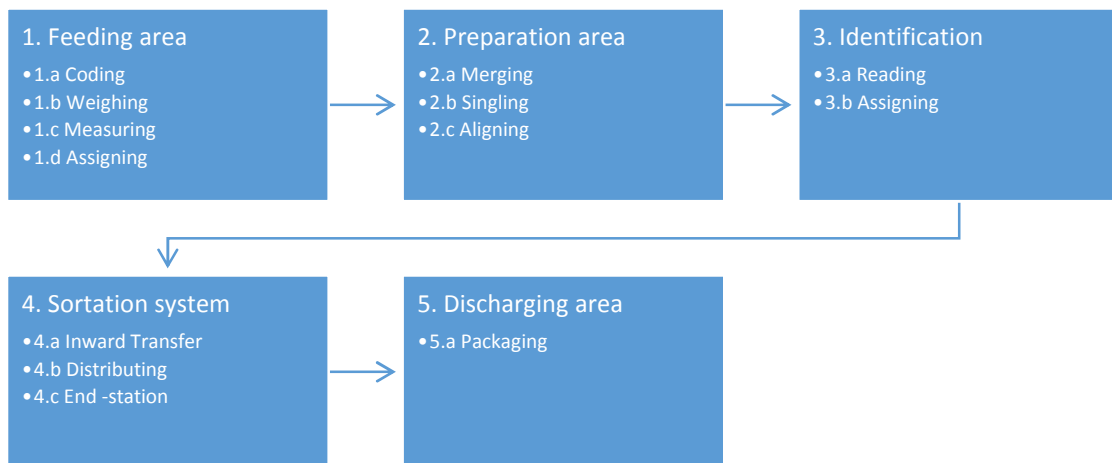
Figure 6: Structure of a sortation plant [JtH05]

Sortation plants can be broken down into five different functional areas that summarize different functions. The following subsections one to five give a closer look on these functions and highlight some specific examples.

1. Feeding area:

    The feeding area represents in material flow the input interface (a: coding, b: weighing, c: measuring and d: allocating). The scope of supply also contains the vibrating conveyors for the feeding of the product and the basic engineering. Continuous charging means that the goods run in in firmly order and frequency on an ascending conveyor. If a truck unloads the goods directly on an infeed area, so that the goods build a bulk or the parcels are placed manually, this kind of feeding is called bulk charging [JtH05].

2. Preparation area:

    Merging, singulation (separation) and alignment or branching are disciplines of preparation like automatic identification and discharging. The cargo should not lie side by side and should hold a minimum distance. Normally the packages should run into the sorter in a defined orientation.

a. Merging: To merge the goods, deflectors or discontinuous belts are used. They unite more than two good flows on a main gate, chamber-like reunifications are used, with an angle of 35° to 45° [JtH05].

b. Singulation: This operating process represents the nucleus of this master thesis. The following paragraphs give a rough overview on the singulation procedure with the target of clarifying the framework of this separation method in distribution centres. In chapter 2.4 follows the methodological classification of singulation processes by the help of product screening and patent research for providing a deeper insight on this topic. The different solutions from several industries will be clustered according "their predominant effect of working principles" [FWL+15].

A typical mechanical singulation mechanism can be caused, when goods are transferred from a slow to a fast continuous conveyor belt. The first parcel gets more speed by the transition so that the space between the parcels enlarges. To regulate the distances between the goods, single powered conveyors are needed, which create optional distances over sensor technology and control. Separation also often means to dissolve side by side good flows on one conveyor and create a uniform orientation [JtH05].

Figure 7 shows a simple mechanical solution for merging, separation and alignment of a good flow over diverse autonomously powered conveyors with different modes of operation [JtH05].

Two good flows run in clocked or non-clocked from the left side into the preparation area. The conveying velocity rises from conveyor to conveyor, to increase the interspaces between the parcels. The inclination of the angular roller conveyor leads the goods to one side (down). Unequal lever arms and angles from the deflectors have a different effect on the packages during the singulation procedure and thus affect the result significantly ([JtH05], [FWL+15]).

The angular roller conveyors two, three and four have additional conical rolls. The goods on the side with a bigger diameter (upside)

are moving faster and can fill the gaps in the good flow. The throughput is up to 8,000 pieces/ hour [JtH05].

An in-line arrangement is not really space saving. An alternative is a circular arrangement that leads goods, which are not in the right position to the start of the circular flow [JtH05].
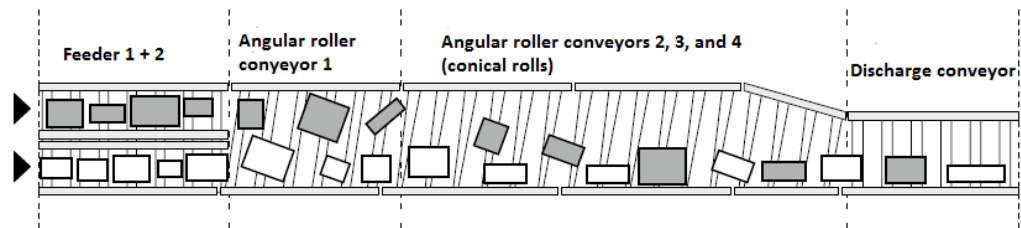
Figure 7: Merging, singulation and alignment without circulation [JtH05]

Figure 8 illustrates two distinct systems for different services. In version a (left), the singulator positions the goods along on one side. The goods in the "side-by-side remover", which are in second line, are put into the recirculating conveyor. The flow controller has two belt conveyors in row, which are separating over different velocities. Side by side laying or undue goods are also removed into the recirculating conveyor, which puts the separated goods back to the inlet. Another capability of this system is to briefly buffer peak loads. This happens mainly over the recirculating conveyor.

The system shown in b (right) is for smaller packages. You can see three different areas in row, with recirculating conveyors on both sides.

It´s visible, that the recirculation needs space till the goods are separated and aligned. With the use of image processing systems and active movement manipulation, the desired position and layer of the goods in short time and space has been feasible [JtH05].
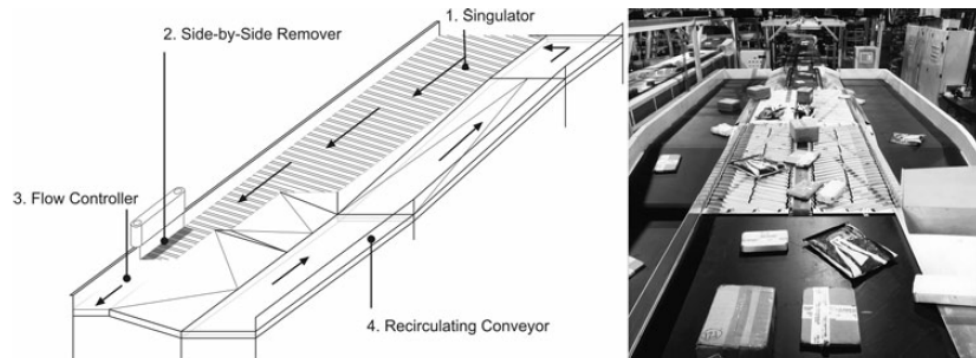
Figure 8: Merging, singulation and alignment with circulation [JtH05]

The singulator "Visicon" from Siemens in Figure 9 is based on this concept [SIE09]. The singulation process starts in the same way as in other systems with a unsorted parcel bulk. After infeeding, the parcels start to slow down, speed up, build gaps between them or spin around. In this way, the parcels line up in single file and orderly spaced. This is possible because of the use of special cameras, an image processing system and individually guided conveyor belts. In a first step, gappers create the required gaps between the parcels at right angle to conveying direction. A transfer belt stabilizes the parcels before entering a light barrier which records the base area and relative position of each package. Cameras take a snapshot which is sent instantly to the computers. With advanced algorithm the computers calculates how each single parcel can reach its target position. The computer sends the information to one of the 84 individually guided conveyor belts which convey every parcel independently analogous to the computers instructions. Cameras record the modified position of the parcels again and trigger further adjustments. The conveyor belts move each parcel individually, slowly and reliably into the perfect position which was calculated by the computer. This permits that no recirculation is available or any manual intervention because all parcels are arranged in a steady row and are ready for further steps. This system is able to singulate up to 9,000 packages per hour [SIE09].
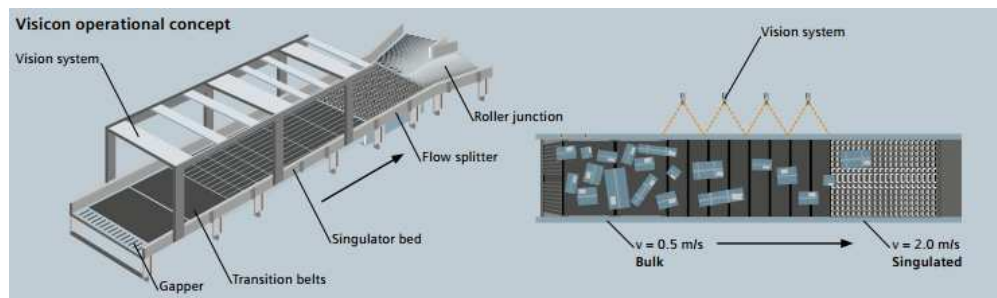
Figure 9: Singulator Visicon from Siemens [SIE09]

    c. Alignment or branching: Another mode of the preparation area is to bring goods into the right guidance for inward transfer. This can happen before or after identification. For a horizontal inward transfer the goods have to have a specific angle, so that they lay optimally on the sorter [JtH05].

3. Identification:

   After cargo singulation and the alignment follows the identification. It basically consists of two steps, read Identcode and assignment to an end station. Identification can be either the barcode with almost 70% of the application or with RFID transponders. If the identification is made via barcode, it has to be warranted, that the goods have been aligned correctly in the area of preparation, so that the barcode can be read by the scanner. High quality identification is feasible by implementation of multiple scanner devices in a huge reading domain with high depth of focus [JtH05].

4. Sortation system:

   Sortation means building subsets out of an unsorted amount of objects so that the classified objects have one or more unifying characteristics. These characteristics can be numerical (numbers), physical (weight, shape, colour) or alphanumerical (destination address) [AF09]. Generally sortation is the identification of object characteristics and allocation to classes. The sortation of the cargo to the end stations is realized technically by

sorters [JtH05]. Figure 10 outlines the flow chart a sortation process. The individual piece goods (parcels) of a certain number of charging lines "m" have to wait "W" before they could infeeded to the so called sources "So" that are elementary stations of the type (0, m), from which m of outgoing flows move out. These flows are merged in "M", before every piece good is identified in "I" and branched in "B". The piece good flow is further conveyed to discharging points "DP" and ends in so called drains "Dr" that are elementary stations of the type (n, 0), in which "n" of incoming flows end and possible existing outgoing flows are not considered [AF09].
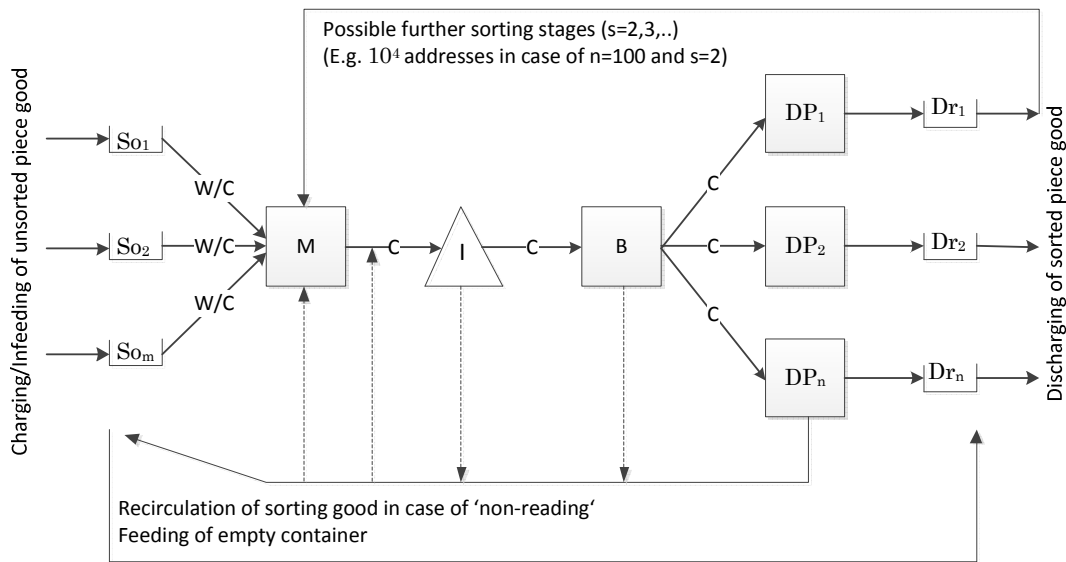
Figure 10: Flow chart of the sortation process [AF09]

Merge elements like switches, turntables, converters, tilt tables, or lane branches combine several (m) partial intake streams to a discharging stream. Branch elements are merge elements that are working in reverse direction; they divide an intake stream into several (n) partial discharging streams. Examples for sources are raw material warehouses, palletizer, incoming-, service-, filling-, or charging-stations, which are characterised by the service rate of the process. Examples for drains are disposals, warehouses, outgoing-, consumption-, machining- and disassembly-stations, which are determined by a consumption rate that is determined via the cycle time and the batch size of the process [GUD05].

a. Inward transfer:

This operation is often executed manually due the fact that piece goods have to be aligned in right position and with correct orientation for downstream conveying devices. The inward transfer is differentiated due to arrangement and degree of automation [JtH05]:

  i. Arrangement:

  It depends on the distribution conveyor, which arrangement is adapted for inward transfer. Following three arrangements are used for conveying equipment [JtH05]:

    o Frontal inward transfer
    o Vertical inward transfer
    o Horizontal inward transfer

  ii. Degree of automation:

  It is determined by the state of technology from controlling-, sensor- and conveying equipment, it can be distinguished between following three degrees of automation [JtH05]:

    o Manual inward transfer
    o Semi-automatic inward transfer
    o Fully automatic inward transfer

b. Distribution conveyor:

The distributer is the key component of a sortation system. Conveyor, suspension element and outward transfer mechanism exist in every distribution conveyor in individual specifications.

c. End-station:

Size and fragmenting of end-stations depend on kind and amount of assignments. Main tasks are gentle and steady discharging of goods, manual taking off of the goods from the sortation process, automatic transformation to conveying or manufacture processes and the storing up of goods [JtH05].

The sortation of piece goods is one of the most expensive working processes in logistics [JtH05]. Huge sortation units do have the advantage of being more cost efficient than smaller ones, the degree of capacity utilization is more balanced and it offers the opportunity of a great automation level. For being economical and reach a high level of automation at the same time, a high minimum throughput is required [AF09].

5. Discharging area:

It characterises the last technical step in the sortation plant and assumes the task of packaging. Either the goods are transferred from the end-station to downstream material areas or the end-stations are discharged by manual or automated packing areas, to make them conveyable. Discharging of packaged and labelled goods of the packing area is not part of the sortation system anymore [JtH05].

2.2 Application/Selection-Criteria for Sortation Systems

Different criteria must be considered for selecting and planning of sortation systems. In general, designers of sortation systems have to consider four different aspects for the optimal application of a sortation system [JtH05]. Figure 11 lists specific characteristics of each aspect, which should be fulfilled in the planning stage of distribution processes in the CEP-sector. Especially cargo-specific criteria significantly affect the singulation process of parcels.

System-specific	Cargo-specific	Organizational	Overall
sortation performance	shape	operating mode	space requirement
conveying speed	physical dimensions	charging method	constructed size
distribution conveyor length	stability	deployment of personnel	costs
number of end-stations	weight		environmental noise
discharging positions	position of centre of gravity		expandability
arrangement of end-stations	friction behaviour		availability
storage capacity			energy efficiency

Figure 11: Eligibility criteria for sortation- & distribution-systems [JtH05]

The system-specific criteria arise decisively from the field of application of sortation systems. Singulation mechanisms in different industries must meet system-specific criteria. The CEP-sector focuses on the required effective sortation performance (up to 50,000 parcels per hour) ([BIE15]; [CRR+14]). The technical limiting performance is usually not reached over a whole day. Flexible systems represent the planning target because they can adapt to short-term throughput fluctuations and allow for long term expansion and reduction [JtH05]. The conveying speed influences significantly the sortation performance. Higher velocities imply higher performances. The required length of conveyors depends on building- and system topology as well as on the number of needed end-stations [JtH05]. The arrangement of end-stations can be realized in linear or circuit layouts, on one or both sides [JtH05].

The organizational and operating strategy of the CEP-sector includes mainly the mode of operation (continuous or batch mode). It has an influence on layout- and operational-performance (e.g. number of end-stations) [JtH05].

The selection process of sortation systems for distribution centres in the CEP-sector has to consider additionally overall criteria. The space requirement represents one of those criteria, it indicates the floor space of the system in the operating room which cannot be used for other facilities e.g. production or storage [JtH05]. The expansion capability refers to number of end-stations, inward

transfer areas, vertical alignment and length of distribution conveyors and how these components can be expanded [JtH05].

Cargo-specific criteria define the basic parameters for cargo more in detail. These criteria are very crucial for the singulation of solid bodies in different sectors (e.g. food-industry in subchapter 2.3.2:

- The shape of the cargo has an effect on the storage stability. Cuboid packages are very solid, cylindrical, conical or globular packages are rather instable. Little disturbance forces change their layer [JtH05].

  Figure 12 demonstrates the basic differences between piece- and bulkgoods. If a system handles with bulk goods, it is unavoidable to calculate a volume flow rate. In case of piece goods, the pieces are countable and it is possible deterring a maximum throughput. The formulas for both kinds of cargo are listed in the following sketch including the required variables in the green box [GUD05].

Volume Flow Rate: $\dot{V} = A * v_F \quad \left[\frac{m^3}{s}\right]$

Mass Flow Rate: $\dot{M} = \rho * A * v_F \quad \left[\frac{kg}{s}\right]$

$V = Flow\ rate \quad \left[\frac{m^3}{s}\right]$

$A = Cross-section\ area \quad \left[m^2\right]$

$v_F = Conveying\ speed \quad \left[\frac{m}{s}\right]$

$\dot{M} = Mass\ flow \quad \left[\frac{kg}{s}\right]$

$\rho = Density \quad \left[\frac{kg}{m^3}\right]$

$\lambda = Throughput \quad \left[\frac{1}{s}\right]$

$m = Bulk\ weight \quad \left[kg\right]$

$s = averaged\ bulk\ distance \quad \left[m\right]$

Throughput: $\lambda = \frac{v_F}{s} \quad \left[\frac{1}{s}\right]$

Mass Flow Rate: $\dot{M} = \frac{m * v_F}{s} \quad \left[\frac{kg}{s}\right]$
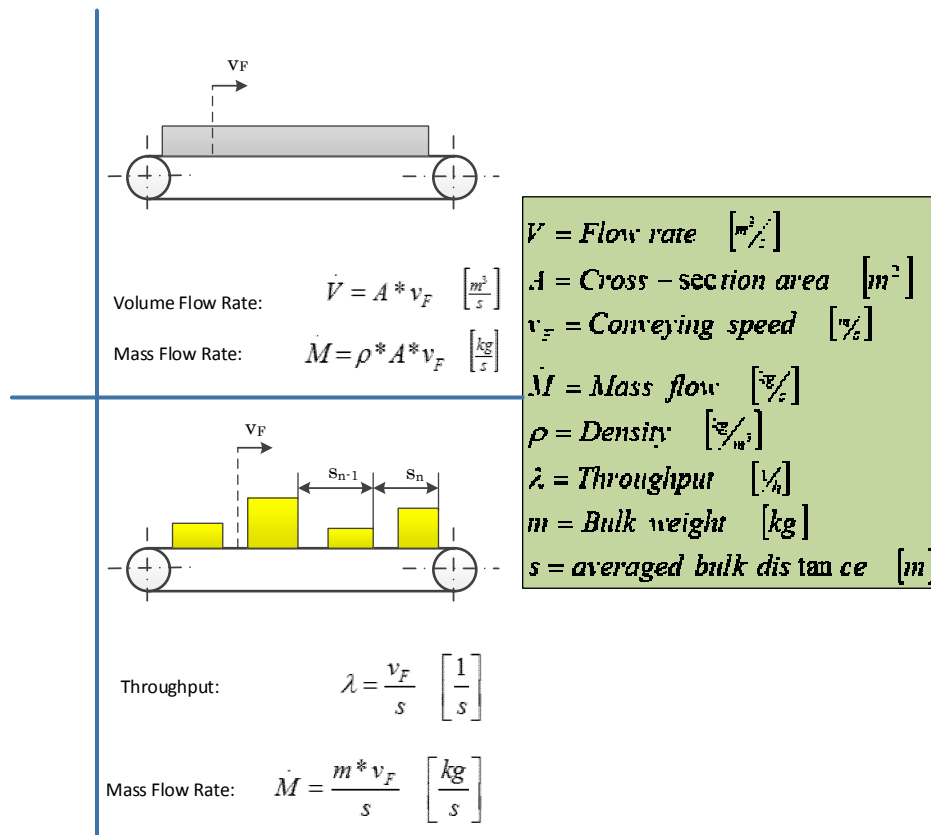
Figure 12: Flow rate and throughput of continuous conveyors [AIK04]

- The dimension of the material relates to the minima and maxima of length, width and on the girth. Dimensions have an impact on the sorter, end-stations and conveyance, as well as on the throughput. The longer the sorted goods, the bigger the curve radius, end-station's width and occupied space on the sorter. The maximum height has an effect on the reading system especially the scanners, because the reading distance increases the smaller the packages are. In vertical inward transfer, the maximum height influences the drop height of the goods, as well as the goods width has an effect on the conveyors and end-stations widths [JtH05]. Piece goods are individualized, distinct goods that are handled individually and their stock is managed piecemeal or as a container. Table 2 gives an overview of the standard sizes from parcels which are used from the Austrian Post [POS15].

Table 2: Standard sizes of parcels [POS15]

Dimension	Small	Medium	Large	Extra Large
Size outside	320x220x105	400x310x140	380x305x250	550x360x325
Inside size	262x200x95	345x290x130	315x287x244	486x341x313

- Stability of goods: It contains two aspects. For the sorter, shape permanency and stability with force effect are important. For the goods, the sorter specific load by splicing, speeding up and compressive force are relevant [JtH05].

- Weight of piece goods influences the applicable discharging technique. Discharging periods getting shorter, the increase in speed across to direction of motion raises, which lead to higher discharging forces the heavier the goods are. Also minimum weight is important to avoid lifting and too high speed [JtH05].

- Centre of gravity position is important for rollover stability. The rollover stability has to be guaranteed also by high speed sorters and close curve radius. A low and stable centre of gravity is favourable [JtH05].

- High frictional behaviour is requested during transport for holding the goods in position when dynamic forces act on a pile of piece goods. The frictional behaviour has to be minimized in discharging areas for guaranteeing fast discharging via sliding effects and safe motion in end-stations [JtH05].

Sortation systems in many industries are based on those criteria. The following chapter shows the application of these criteria in different sectors and summarises the current state of the art.

2.3 State of the Art

There exist some approaches for the singulation of piece goods on the market, but these singulator solutions do not satisfy in all considered areas [FWL+15]. The most common problem depicts the high price/performance ratio that requires the simplification of technical concepts [INT15]. The operating range of a specific type of singulator regarding homogeneity/ inhomogeneity of the dimensions of incoming piece goods is often very limited ([SIE13]; [BEU14]).

The objective to manipulate previously undefined parcels from a bulk under visual control is one of the main tasks for the implementation of a mechanical separation based material handling system. The automation of such complex industrial surroundings requires the improvement and adjustment of existing approaches like the waterfall scenario for guaranteeing high adaptation and capability in dealing with parcel piles [WB96].

Mechanically based parcel singulators transform a parcel pile into a regular flow that consists of a manageable single-filed array. This operation is realized via skewed rollers, friction belts, slides, waterfalls, flexible barriers (curtain), grapping robots, deflectors, or other mechanically based working principles. The sin-

gle-filed parcel flow at the end of the singulation procedure feeds downstream sortation devices and stabilizes the further material flow in a distribution centre (optimisation of cargo density). Figure 13 represents the process model for a whole sortation system, including in- and out-feeding streams [FHS12]. One or more infeeding belt conveyors supply the singulator with packages.
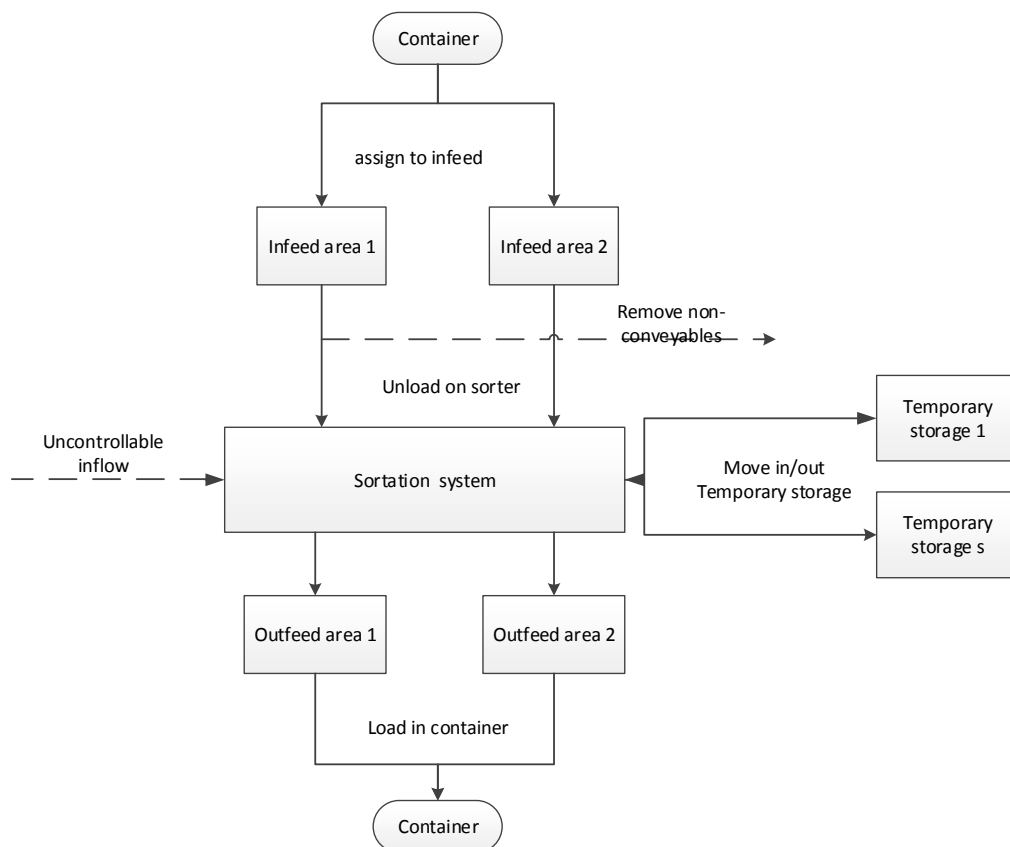
Figure 13: Process model [FHS12]

The feeding process builds the interface between container and infeeding areas, it contains the operating steps unloading, singulation and transfer [FWL+15]. The chain of goods receipt processing is not fully automated, but there exist some robotic technologies. Figure 14 illustrates the "ParcelRobot" from ThyssenKrupp Krause that is based on an individual gripper system for automatically palettizing of unloaded parcels [TKK15]. The intelligence of this parcel robot is achieved by three major components: the "eye" as 3D-scanner, the "brain" computes the gripping points and the "sense of touch" compensates fluctuations between eye ansd brain by the help of close range sensors [TKK15].

This approach unites several advantages but comes at a price, whereby this master thesis aims the consideration of simpler singulation mechanisms.

Figure 14: Parcel roboter [TKK15]

2.3.1   Construction of a Singulator: An Example

Figure 15 shows the singulator setup of a vision system, which has the task to compute the corner points of all parcels to guarantee that the singulator transforms a parcel heap into a single-lined output stream. If the singulation-degree (see Figure 62) is too low, the vision system sends failure information to a controller and the inspector has to intervene in the singulation procedure. This singulator can be distinguished in four major components [KA05]:

1. Gapper
2. Transition belts
3. Singulator bed
4. Diverter
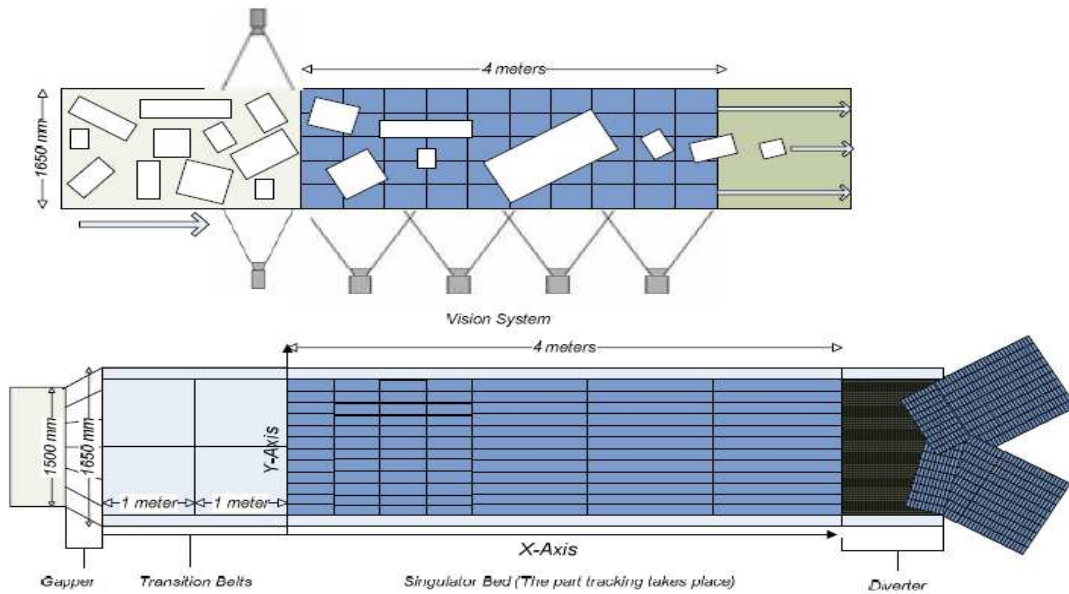
Figure 15: Different views of the singulator [KA05]

2.3.2 Approaches from other Industries

Low cycle times in piece good handling often have the consequence that there is not enough time for processing individual pieces by a robot. It comes to idling regarding no-load operations like approaches and returns of robots (empty trips). Therefore, new approaches and innovations are needed for transforming an unorganized bulk of piece goods in an orderly flow of solid bodies. Depending on the type of piece goods and process specific constraints, different solutions or modified systems are required. The following two examples do not cover the singulation procedure in the CEP-industry, but they handle with this topic in other sectors. The objective of this consideration is to transform these approaches on the field of parcel singulation and to cluster the predominant effects of the working principles in the different industries [FWL+15].

Food industry:

For the quality assurance in the food industry like prevention of cereals against mould, it is inevitable to singulate a bulk into a manageable single flow. The sifting of damaged grains is then processed by the help of automated image analysis. If more than a half of the surface from a grain is coloured conspicuously, it shall be considered as damaged and it must be sorted out [mCi15].

The apple industry assures their quality in term of a simplification from 3D to 2D. The optical quality characteristics are checked by dipping a certain number of apples into a pool of water, so that they are driven by the buoyant force on the water surface. It follows a simplification of the singulation from a volume to a surface and possible sources of errors are minimized. This waterfall-approach was introduced in the apple industry via the singulator from Erik van Wijingaarden and Tom Delfos [DvW04].

2.3.3 Already Examined Singulation Scenarios

The transformation of general bulk material to countable piece cargo requires the use of an appropriate numerical method [BLO08]. The use of the Discrete Element Method (DEM) and Multi Body Simulations (MBS) brings both kinds of conveying goods closer together and allows the assumption that parcels can be handled as a bulk material. For the realization of a certain throughput in a material handling system, it is crucial to clear jammed and dammed parcels from a bulk. This objective requires a successful implementation of proper conveying principles that realizes a nearly faultless transportation of a large amount of parcels [CRR+14].

The rough singulation of parcels should result from falling of a bulk on a lower positioned conveyor belt ([FWJ13]; [FWL+15]). After this so called "waterfall scenario" further singulation mechanisms like deflecting are processed. The following two subchapters clarify the essential characteristics for both singulation scenarios. Based on the slightly simpler singulation in the plane (2D) in the first mentioned scenario, in the second point is dealt with the more complex singulation in a domain (3D).

2D-deflector:

A deflector has the task of controlling the orientation of parts by deflecting a conveyed stream of pieces in a plane (2D- two dimensional). The deflector converts a multi-filed bulk goods conveying stream into a continued single part goods row. Bernd Möhle developed in his dissertation lay out design criterions for deflection principles of load unit conveyor systems. He distinguished the movement of a piece good like a parcel during deflection operation into five phases [MÖH83]:

a. **Phase 0:** the single load rests relatively to the conveying good and moves with conveying velocity.

b. **Phase 1:** the single load pushes with conveying velocity against the deflector and its impulses are being changed by this push.

c. **Phase 2:** the single load is located with one corner at the deflector and makes a movement, consisting of rotation and translation or just a rotating move.

d. **Phase 3:** the single load pushes with one side against the deflector and its impulses are changed.

e. **Phase 4:** the single load is located with one side at the deflector and makes a pure translation movement.

Figure 16 demonstrates the intensity of conventional calculation for all five phases of a single parcel movement during deflection operation. A variety of angular relationships and mathematical conditions are needed to describe this system. Therefore, the application of simulation tools for investigation singulation of piece goods offers the advantage of being more cost and time efficient than real experimental setup. In addition parameter studies are possible which quickly lead to results and allows statistical researches in validated simulation models. With reasonable computing time and effort, the behaviour of a piece good bulk with changing piece configuration can be examined regarding to shape, size and weight to be able to make statistically relevant conclusions.
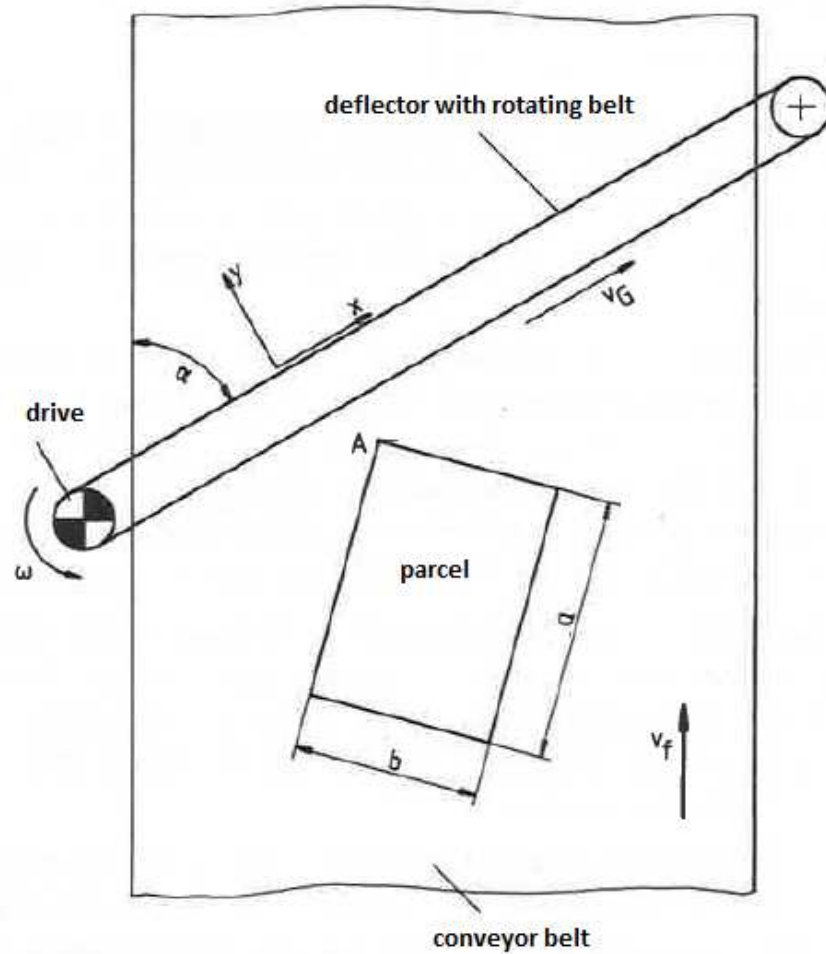
Figure 16: Deflection principle with rotating belt [MÖH83]

The simulation tool has to fulfil particular requirements: it has to be feasible simulating the interaction of a big number of pieces. Typical equipment of the conveyance, which has an effect on the behaviour of the parcels, has to be integrated into the simulation model. Furthermore, the simulation tool has to exhibit a contact model, which reproduces realistic interactions behave of the pieces. The configuration of parcels in the bulk varies, whereby the simulation tool has to compute random arrangement as well as concretely favoured parcel arrangement (e.g. parcel tower). Acceptable calculating times are an additional prerequisite on the simulation tool. The expansion from 2D to 3D-singulation consideration requires a new factor screening; therefore it is unavoidable to use a simulation tool for this examination [FWJ13].

2.4   Methodological Classification of Singulation Processes

A working principle describes regularities of a technological process. The interaction of physical effects, geometric and material characteristics describes the natural scientific, technological and technical operations of a process. The combination of working principles from sub-functions leads to the fulfilment of an overall function. The development of a working structure is possible, if the working principles from each sub-function are assembled. The concretization of the working structure enables a general solution finding [PBF+06].

Following three basic principles of mechanical joints must be taken into consideration for mechanical singulation of a bulk of parcels:

1. Material joint: It is carried out by material joining on parcels surfaces or additional materials from environment on molecular- and adhesion-basis under high ambient temperatures [PBF+06]. The operating temperature in distribution centres can be regarded as relatively constant; nonetheless, this kind of joint cannot be neglected for the mechanical singulation of parcels because plastic sheeting is used as packaging material [DHL15].

2. Form-joint: It is effected by normal forces of interlocking active surfaces of jammed and dammed parcels in a parcel heap under absorption of surface pressures and resulting stresses in the contact zones according. [PBF+06]

3. Force joint: It is effected via the action of forces between the working surfaces of accumulated parcels in a bulk. Forces can be caused by different physical sources; therefore, it can be distinguished between several types of force joints [PBF+06]:

   a. Frictional force joint: It is caused by frictional forces F_r on the working surfaces of the parcels. These frictional forces are caused by normal forces F_n, e.g. according Coulomb's law of friction: $F \leq F_r = \mu_H * F_n$ [PBF+06].

The frictional forces restrict the transmission from this kind of force joint; μ_H quantifies the coefficient of adhesion.

b. Field force joint: Examples are magnetic forces in magnetic fields, compressive forces in hydro- and aero-static or viscous forces in viscous media [PBF+06]. This kind of force joint is also relevant for the mechanical singulation of a parcel bulk, e.g. the design and implementation of robotic parcel-sortation systems is based on grapping by robot arms that underlie the pneumatic principle [YYJ+14].

c. Elastic force joint: The parcels cannot be assumed as completely rigid, because the parcels will be minimally deformed after the impact on the lower conveyor belt in the waterfall scenario in Figure 19. Therefore, each of the "elastic" parcels determines in this manner the position and dynamic behaviour of the other involved parcels during singulation procedure. This complexity requires the use of an appropriate simulation tool with a suitable integrated contact model, which will be described in point three of subchapter 3.2.1.

The singulation process has the aim to optimize the density of the parcel-flow, which is increasing every year due to booming e-commerce [ITL14]. The cargo density ensures that there are always a sufficient number of parcels on the respective conveyors. If the cargo density is stable, there is no idle running in the material flow. Following criterions define the successive separation of a parcel heap into a straight-lined parcel flow with defined distance in between:

- 3D to 2D → no package is positioned on the other, a domain is reduced to a plane, e.g. no parcel towers on the conveyor belt

- 2D to 1D → an arrangement of packages on a plane like a conveyor belt is transformed to a straight-line flow in one direction.

Figure 17 gives a closer look on the singulation procedure from a parcel pile into a single-filed parcel flow. This flow chart defines the dimension of certain parcel arrangements. Examples for a 3D-arrangement are bulk cargo like parcel accumulations in containers or a parcel tower that is examined in the practical part of this master thesis. These kinds of accumulation require the highest effort for converting it in a 2D-parcel arrangement. The disarrangement in the plane (2D) necessitates lower singulation effort because the problem was reduced by one dimension and could be solved via deflectors. If the deflectors have transformed the disorder into a regular parcel flow with defined gaps in between, the 1D-arrangement provides a stable material flow with low error sources. The 1D-parcel flow represents the desired status quo within distribution centres ([AF09]; [BEU14]).

3D-arrangement
- one or more parcels rest over each other and/or more than one parcel tower
- a maximum of two parcels over each other and only one parcel tower

2D-arrangement
- all parcels overlap normal to the moving direction
- no single-filed parcel stream, e.g. no defined gaps between the parcels

1D-arrangement
- no parcels overlap normal to the moving direction, but all parcels are in contact
- no parcels overlap normal to the moving direction and any parcel touches another

Figure 17: Procedure of the singulation process

Table 3 shows the special arrangements of parcels after unloading on a conveyor belt which has been mentioned in the previous flow chart. For the singulation from 3D- to 2D-arrangement, a pile of parcels has to be singularized to a two-dimensional grid by the help of a waterfall. For the singulation from 2D- to 1D-arrangement, a grid of parcels is singulated to a one-dimensional single-filed row by the help of velocity changes and deflecting elements.

Table 3: Special arrangements of parcels
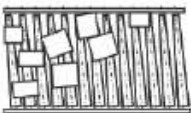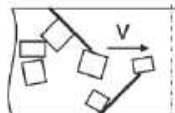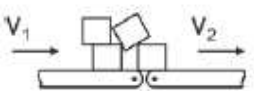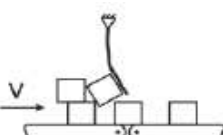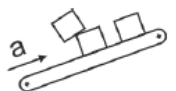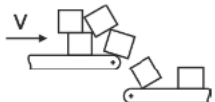
The singulation methods, listed below, can be adopted for the singulation of solid bodies in different industries. This list is not complete and can be extended by other methods that are primary based on form-, force- or frictional force joint:

- 3D-to 2D: waterfall, flexible barriers (curtains), grapping by robotic arms, buoyancy force for objects of low mass, …

- 2D to 1D: acceleration/deceleration, different friction fields (between parcel-parcel or parcel-conveyor), change of direction (curved conveyors), vibration, centrifugation, filtration, …

The experimental investigation of this master thesis deals with the singulation from a parcel pile to a two-dimensional parcel arrangement. Most singulation processes handle with separation approaches from 2D to 1D. The CEP-industry is searching for singulation solutions from 3D to 1D, because there are only robots for the unloading and separation operation on the market [FWL+15].

Matthias Fritz clustered in Table 4 the different singulation solutions due to the "predominant effect of the working principle" [FWL+15]. The predominant effect of singulation mechanisms can be distinguished into surface- and body-forces, whereby surface forces are composed of frictional- and normal forces [FWL+15]. This evaluation matrix assesses also the achieved dimension of each singulation mechanism, e.g., subsequent belt conveyors with vertical gap (waterfall) singulate a pile of parcels (3D) into a two-dimensional arrangement, if the lower conveyor belt is assembled with some additional deflecting elements, it could also achieved a singulation from 3D to 1D (dashed line).

Table 4: Classification of singulation mechanisms [FWL+15]

Dimenmension	Predominant effect of working principle					
	Surface force				Body force	
	Friction force		Normal force			
1D					with deflecting elements	
2D	different velocity fields	conical rolls	rigid deflectors	flexible barriers (curtain)	inertia force	waterfall
3D						

3 Development of Measures – Procedure

Technical systems that are analysed during development processes are often characterized by a variety of influenceable factors and complex nonlinear relationships. Simulation models of these systems are often simplified by the help of analogous models to minimize computing times. This approximation describes the physical experiment and the derived simulation model with sufficient accuracy. It includes the most significant effects of complex simulation models and is referenced in literature as meta-model [SBH10].

Figure 18 shows schematically a typical procedure of a Computer Experiment (CE) for improving or new development of technical systems.
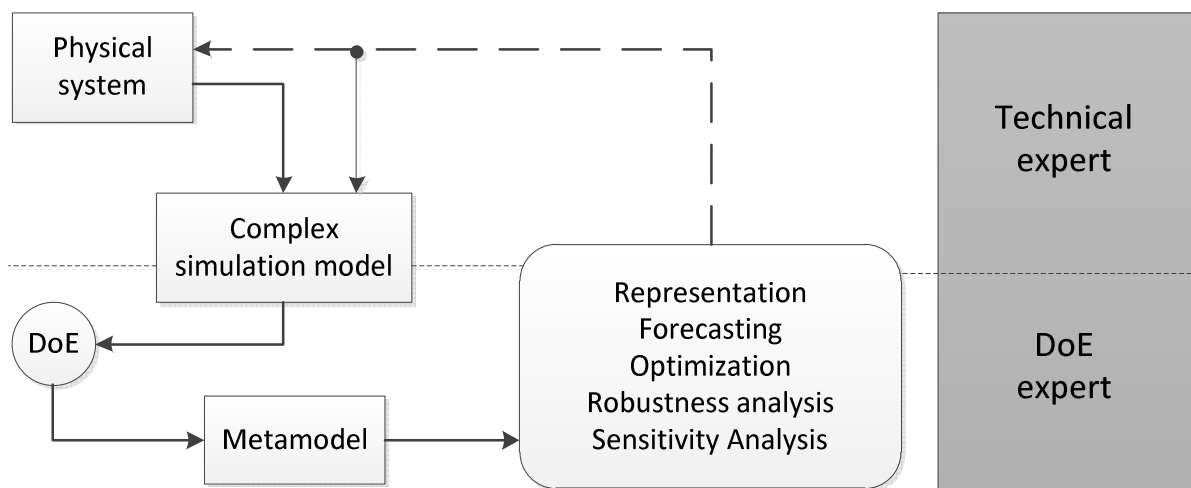
Figure 18: Computer Experiment [SBH10]

In a first scoping study, a complex simulation model is constructed by the help of physical phenomena and the expertise of technical experts. Based on the creation of special datasets (Design of Experiments), it is possible to determine an adequate meta-model for analysing complex and nonlinear correlations between input- and output- factors. The implementation of a meta-model in a simulation tool allows different analysing methods, e.g. representation of correlations with a graph, robustness- and sensitivity-analysis, optimization and forecasting of output parameters. The results and conclusions of these analyses continually

improve the quality of a technical system because recognized weaknesses can be modified in the simulation code. This is usually an iterative process, whereby the number of required iterations is minimized with purposeful applications of experimental designs and algorithms [SBH10].

The present master thesis is conducted according this scheme. Therefore, the experimental setup for the waterfall scenario will be explained in the next point. This physical system enables the measurement of motion behaviour from parcels during falling and acts as validation reference compared to the simulation.

3.1   Physical System, 3D-Waterfall Scenario

Figure 19 illustrates the basic arrangement for the waterfall scenario. A bulk of parcels is located on a upper conveyor platform, which represents the origin of the z-coordinate. The bottom conveyor is offset by the parameter h (height) downwards. In a first step, the height difference causes a rough separation of the parcels from their dense in the bulk and thereby further singulation steps will be enabled. For the sensitivity analysis, it is important to define an initial situation for testing the effects of different influencing parameters during the waterfall scenario. The most important influencing factors are tested by means of DoE at different levels, which has the effect of defining a specific quality feature. This proceeding is discussed more in detail in the following chapters.
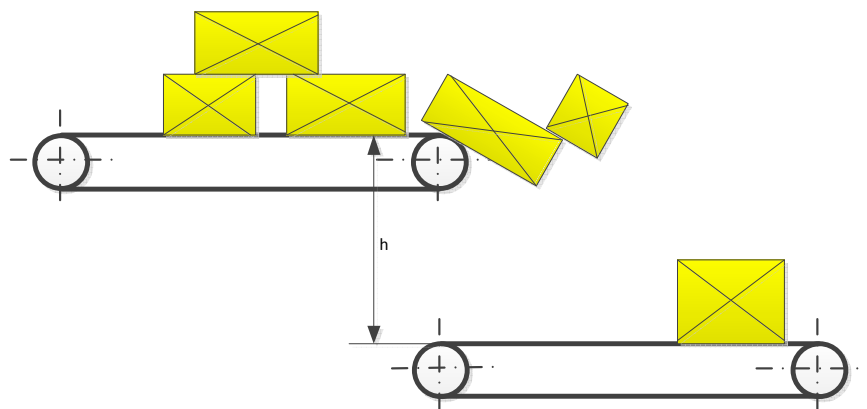
Figure 19: Waterfall scenario

Figure 20 demonstrates the initial situation of a parcel tower for the sensitivity analysis. This parcel tower was brought ten times out of its equilibrium position for surveying the end positions of each individual parcel centre. The waterfall scenario is imitated by the help of a coffee table (height = 0,45m) and four standard Post parcels. One medium sized parcel was positioned twelve centimetres over the table edge; three small sized parcels are piled up flush to front edge of the M-parcel. A minimum external contact is sufficient to disequilibrate the position of rest from this parcel tower and to fall to the ground. For creation of an uniform parcel density and avoidance of displacements of the centre of mass during the experiments, the parcels were filled with wood pellets. The parcels achieved after the filling with pellets a proper mass (medium parcel = 8kg, small parcels = 3,2kg) and imitate the parcel generation in PFC3D (see Figure 33 in subchapter 3.2.2).
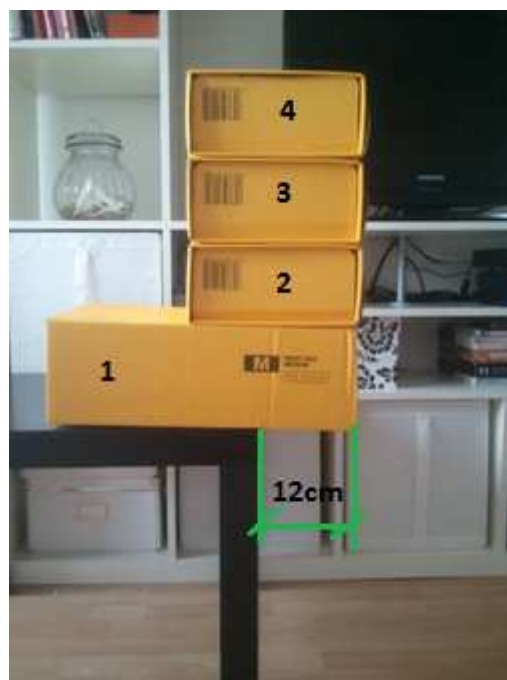
Figure 20: Initial situation

Figure 21 exhibits the end state of the waterfall model whereby the positions of all parcel centres were measured in x-, y- and z-direction. The basic arrangement was for all ten attempts the same: Parcel one rests on parcel two, parcel two lies on parcel three and the two remaining parcels are flush with thee

ground. Table 16 in the appendix records the measurements of all ten attempts, the calculated arithmetic mean of each x-, y- and z-coordinates will be used for comparison with the simulated values in PFC3D.

Figure 21: End state of the waterfall scenario

Figure 22 exhibits the free punch of the lowest parcel of the parcel tower. There were cut free gravitational-, frictional- and normal-forces for the parcel which is positioned directly on the table. From the free punch results the equations for the equilibrium conditions in x- and y-direction, as well as the equilibrium of moments about the instantaneous centre of rotation P.

$$\sum F_x = 0 = -R_1 - R_2$$

$$\sum F_y = 0 = N_1 - N_2 - m_1 * g$$

$$\sum M_P = 0 = R_2 * h - N_2 * 0{,}01 + m_1 * g * \left(\tfrac{l}{2} - 0{,}12\right)$$
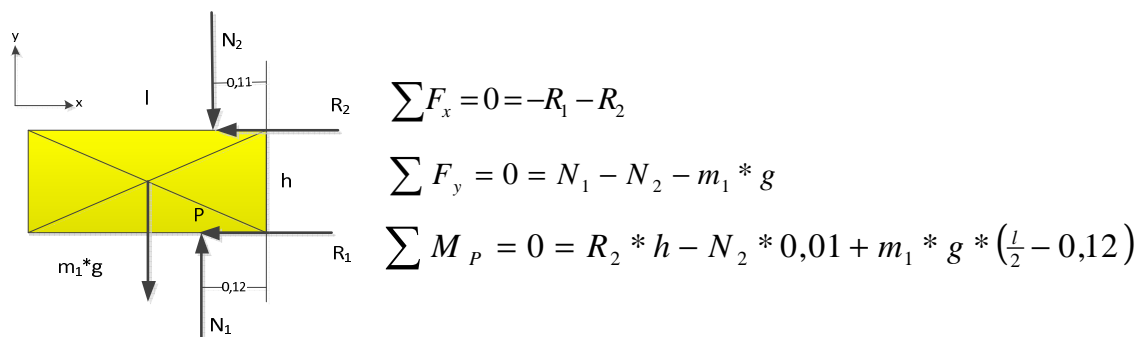
Figure 22: Free punch for the lowest parcel of the parcel tower

3.2 Discrete Element Method

The Discrete Element Method (DEM) is a numerical tool for computing the motion and effect of a large number of small particles. For the simulation, all particles are positioned in a specific starting geometry and provided with an initial speed. From this initial data and the physical laws that are relevant for the particles, the forces are calculated, which act on each particle. Derived forces can be distinguished in two categories [CS79]:

1. Macroscopic Forces (e.g. frictional, gravitational)
2. Molecular Forces (e.g. Coulomb and Van der Waals-Forces)

Figure 23 shows the essential equations that must be solved for each object in DEM. This method represents a typical mesh-free numerical calculation in terms of spatial discretization, which differentiates this method from mesh-based Finite Element Method (FEM). The discrete calculation is based on the consideration and mathematical formulation of individual objects, particles, or walls. The investigation of the mechanical behaviour will be computed only for discretely divided structures or arrangements by the help of explicit numerical problem solving (differential equations). A full system analysis is not feasible because interactions of objects occur only at the contact points [JK12].
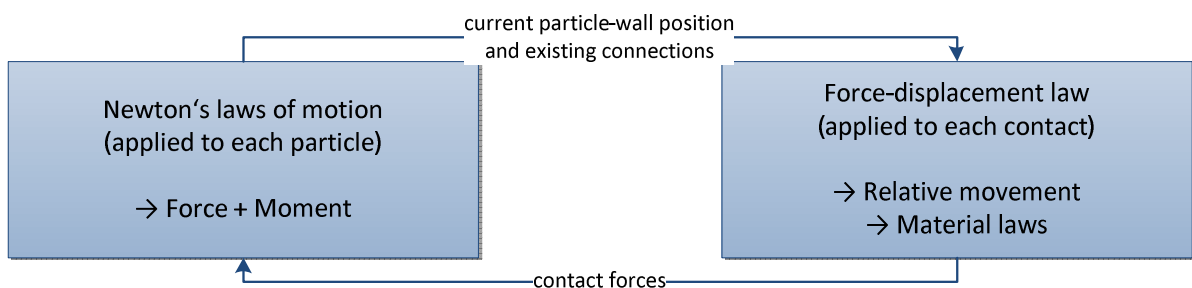
Figure 23: Basics of DEM [ICG15]

An integration method derives from Newton's laws of motion the change of the particle velocity and position during a certain timestep. Thereafter, the forces

are recalculated with the modified positions and velocities and this loop will be repeated until the simulation period is completed. The force-displacement law states that the calculation of the contact forces occurs during interaction through element displacement. Figure 24 represents a flow chart of a well-established loop in a basic DEM-simulation [BHA14].
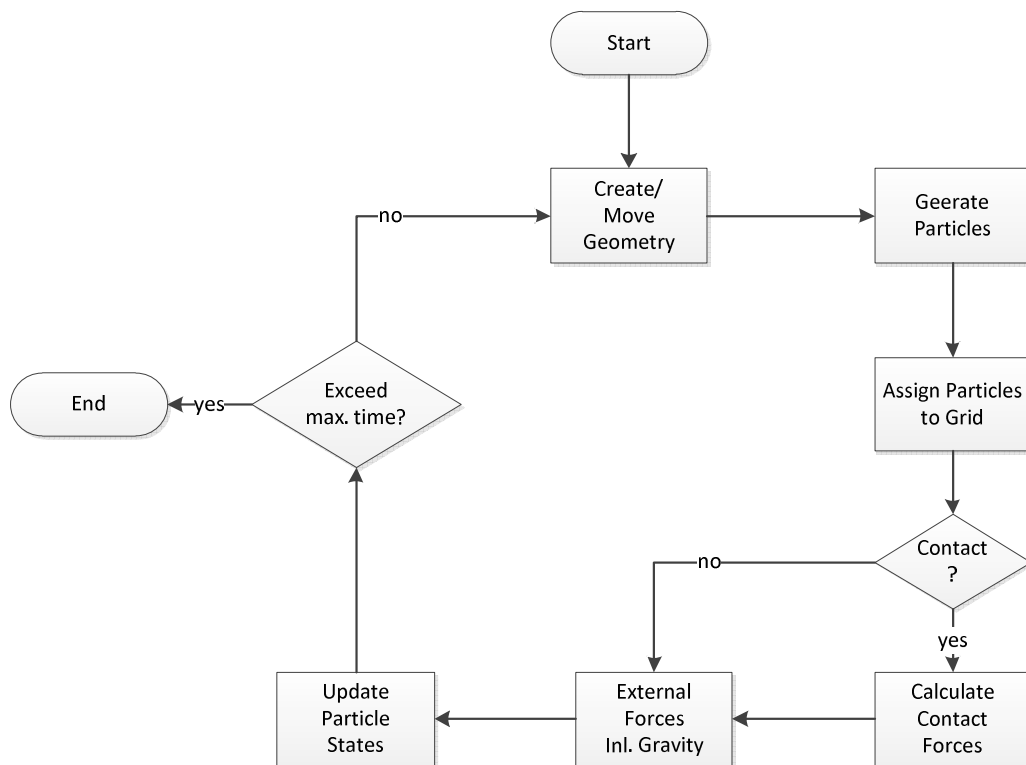
Figure 24: Flow chart of a basic DEM-simulation [BHA14]

Following points must be discussed for the feasibility of a DEM-model [ICG15]:

- Modelling of the geometry
- Definition of the particle properties like density, friction values, contact model
- Generation of particles (size, number, shape, position)
- Continuous computation according initial conditions, which stops on a predefined abort criterion like time, number of calculation steps, reach a state of equilibrium state, etc.
- Representation of the system including measurements

The following two subchapters give on the one hand a closer look on the simulation tool PFC3D in 3.2.1 and describe on the other hand the implementation of the waterfall scenario in 3.2.2. The theoretical points that are mentioned in the first subchapter will be applied in the second subchapter on the waterfall model.

3.2.1   Simulation with PFC3D

Numerical simulations are approximations of the reality whereby input and output uses real numbers like material parameters, initial- and boundary-conditions. Simulations reconstruct the behaviour of a real system to generate knowledge, which can be carried over a real system. The accuracy of the simulation results strongly depends on the quality of the model. Numerical Methods are tools, not solutions unlike analytical methods; therefore it is necessary to validate unknown simulations with a real physical model. The advantages are lower costs and risks and the futility to do the same analysis with a real system ([PBF+06]; [JK12]).

The demonstration version from "Itasca International Company" offers most optional full version features for simulating the waterfall scenario [ICG15]. The following sub-items, listed from one to six, explain the background of this DEM simulation tool and contain the different steps for implementation of the waterfall scenario:

1. Theory and background:

   PFC3D (Particle Flow Code in 3 Dimensions) is a "distinct element code used in 3D-discontinuum analysis, testing and research in any field where the interaction of many discrete objects exhibiting large-strain and/or fracturing is required" [ICG15]. The field of application focuses on the bulk material handling industry (e.g. mining, agriculture), particle formulation processes (e.g. food industry, pharmacy) and mechanical or thermal process engineering (e.g. behaviour of bulk material and transportation operations, fracture processes). PFC as a discrete element code is characterized by the following properties [ICG15]:

- FISH is the embedded programming language for model implementation

- simulates movement and interaction of discrete bodies like a circular in PFC2D and a spherical in PFC3D

- allows complete detachment and identifies new contacts automatically during calculation cycle that will be explained later

- Newton's Law of motion (F = ma) is solved by applying the ODE-solver. The solving strategy contains tree steps: contact detection, calculation of contact forces and the computation of new positions.

- fully dynamic simulation, timestep adjustment is computed automatically by variable timestep solver, according to local conditions

2. General formulation:

A PFC3D model is made up of bodies that interact via mechanical contacts. It consists of two basic entities [ICG15]:

a. Balls, spheres (particles):

    i.   obey and confirm laws of motion

    ii.   interact and cooperate with one another and with walls

b. Walls:

    i.   do not obey and confirm laws of motion

    ii.   used to apply velocity boundary conditions

    iii.   interact and cooperate only with balls

Figure 25 gives a deeper insight into the interface between two pieces that is defined as contact. The interaction volume of both pieces centres the contact plane, which is defined by a location x_c, normal direction n_c and the coordinate system nst. It is oriented tangential to both pieces and rotated for ensuring symmetric relative motion of both piece surfaces. Each contact embeds a force F_c and a moment M_c that act mutually on the two bodies. Positions and relative motion are applied by the particle interaction law that brings internal forces and moments up to date [ICG15].

Figure 25: PFC3D-model (left) and contact plane (right) [ICG15]

The general behaviour of a material like piece good is simulated in PFC by relating a simple constitutive model with each contact. The constitutive model that acts at a particular contact consist of three parts [ICG15]:

a. stiffness model
b. slip model
c. bonding model

PFC3D executes a sequence of operations during every computation cycle. They are listed in a simplified version in Figure 26:

a. **Timestep Determination:** For verification of the numerical stability of the simulation model and the creation of contacts between pieces, the DEM method requires valid finite timestep. Contacts between pieces are superior to points, which are developed from forces and moments between interacting bodies [ICG15].

b. **Law of Motion:** The forces and moments, which are calculated during a defined timestep, provide Newton's law for updating positions and velocities for the next cycle [ICG15].

c. **Advanced Time:** The summation of the current timestep to the previous model time advances the whole model time [ICG15].

d. **Contact Detection:** The creation or deletion of contacts occurs according to the current piece positions [ICG15].

e. **Force Displacement:** The use of a proper contact model supports updates for forces and moments at each contact by using the current pieces-state [ICG15].
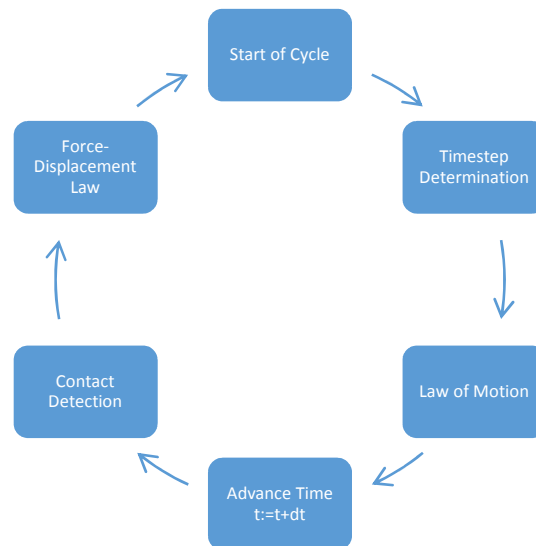
Figure 26: PFC-operation sequence that occurs during each cycle [ICG15]

3. Contact models:

PFC3D generally distinguishes between linear- and nonlinear- contact models [ICG15]. These models define the interaction behaviour between the pairings particle-particle and particle-wall. For modelling contact between particles of the waterfall scenario, the used contact model has to compute realistic contact behaviour within acceptable time limits. The frictional behaviour of the waterfall model can be considered as nonlinear and dry (Coulomb friction coefficient is required). The damping formulation dissipates kinetic energy (parcels do not jump back on their initial height when they fall on the ground).

PFC provides with the Hertz-contact model a solution that meets these requirements [MD53]. This model is based on a non-linear elastic law with viscous dashpots that can be used for impact problems like ball-ball and ball-facet contacts in the waterfall model. It generates normal and shear forces based on the theoretical analysis of smooth, elastic spheres in frictional contact. The model properties including the keywords for describing this kind of contact model are listed in Table 5 [ICG15]. The Hertz group is listed in red background and the dashpot group in green.

Table 5: Hertz model properties [ICG15]

Keyword	Symbol	Description	Type	Range
hz_shear	G	Shear Modulus [stress]	FLT	$[0, +\infty)$
hz_poiss	v	Poisson's ratio [-]	FLT	$[0, +\infty)$
fric	μ	Friction coefficient [-]	FLT	$[0, +\infty)$
hz_mode	M_s	Shear-force scaling mode [-] $\begin{cases} 0: no\ scaling \\ 1: scaling\ is\ active \end{cases}$	INT	$\{0;1\}$
hz_alpha	α	Exponent [-]	FLT	$[0, +\infty)$
hz_slip	s	Slip state [-]	BOOL	{false, true}
hz_force	F^h	Hertz force [force]	VEC	R^3
dp_nratio	β_n	Normal critical damping ratio [-]	FLT	$[0, 1]$
dp_sratio	β_s	Shear critical damping ratio [-]	FLT	$[0, 1]$
dp_mode	M_d	Dashpot mode [-] $\begin{cases} 0: always\ active \\ 1: no\ tension \\ 2: no\ shear\ damping\ if\ s = 1 \\ 3: combine\ modes\ 1\ and\ 2 \end{cases}$	INT	$\{0;1;2;3\}$
dp_force	F^d	Dashpot force [force]	VEC	R^3

Figure 27 displays the current in PFC3D implemented Hertz model that is described by Cundall [CUN88]. This model uses two spring-dashpot responses and a Coulomb friction coefficient μ for producing accurate rests between two particles. The first spring-dashpot response is used for normal contact between particles and/or facets (geometry), the second one for

tangential- and rolling-friction interaction and μ is used for shear interactions. This model uses the initial shear modulus that depends on normal force. This fact leads to the result that this model "does not reproduce the continuous nonlinearity in shear" [ICG15]. That leads to the assumption of a finite sized contact area (relatively small compared with the radii of curvature from the contacting pieces). The contact momentum is equal zero (no relative rotation of the interface) and the contact force is the sum from Hertzian- and dashpot-components [ICG15].
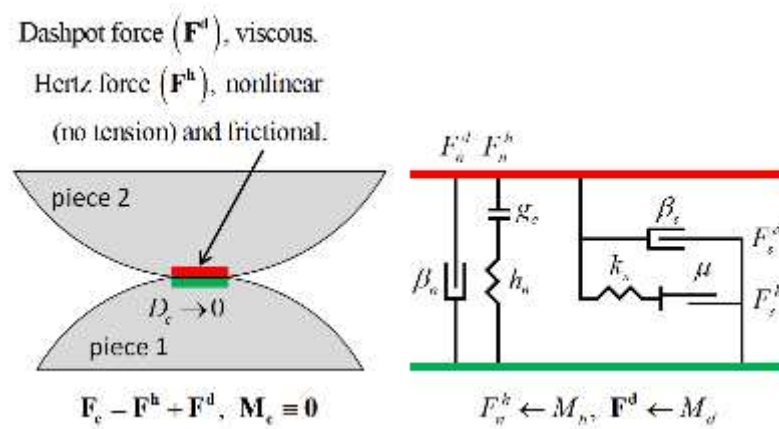
Figure 27: Rheological components and behaviour of the Hertz-model [ICG15].

4. Implementation issues:

The following six phases take place in modelling with discrete elements. The first step contains the particle generation including the definition of a model domain as boundary and initial conditions. The second step includes the determination of contacts between particles and between particles and boundaries. Step three deals with the calculation of forces and moments of all particles, step four calculates afterwards accelerations, velocities, displacements and rotations of all particles. The new positions are calculated in the fifth step, before the last step repeats step two to five with the predefined timestep until the stop criterion is achieved. The PFC3D implementation in Figure 28 is based on those six phases in order to set up an appropriate simulation model.
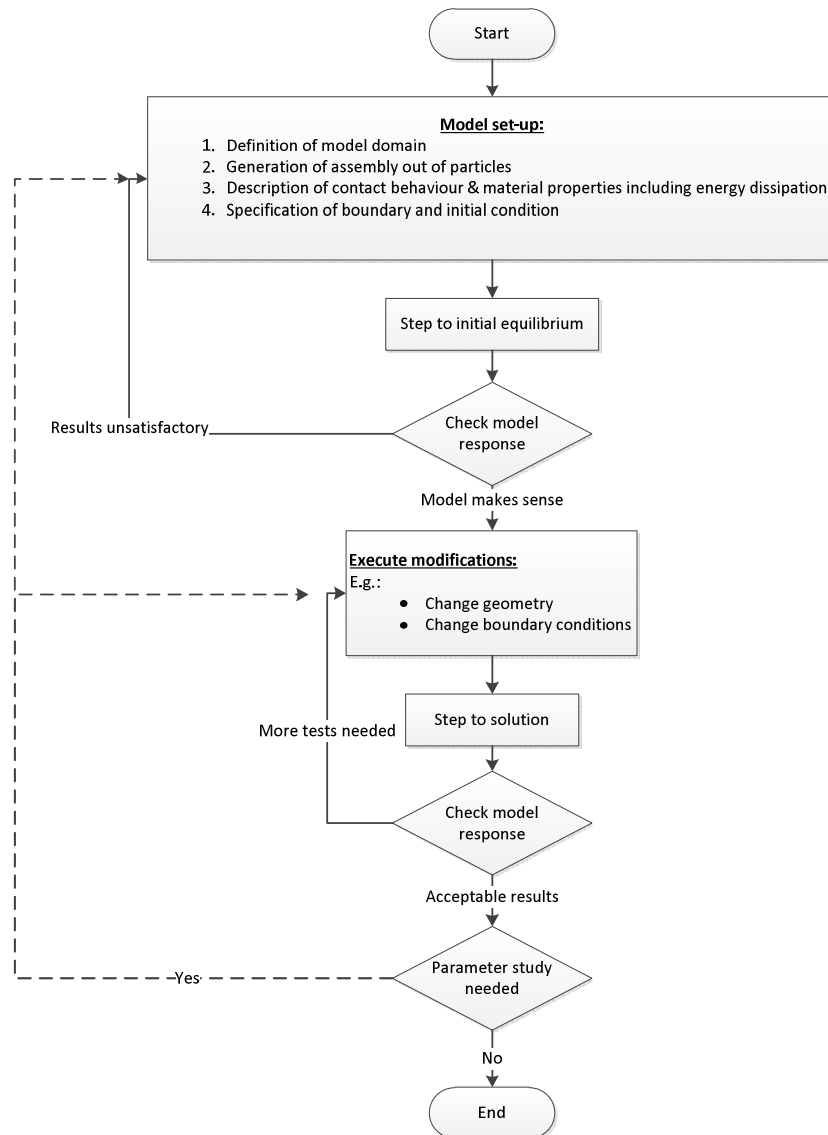
Figure 28: General solution procedure [ICG15]

5. Clump logic:

The positions x^i and radii R^i of pebbles define a surface ($\{x^i, R^i\}$; i =1, 2,.., n) in PFC3D whereby a collection of n rigid spherical pebbles produces a clump. Their motion (translation and rotation $\{v, w\}$) obeys the equations of motion which makes existing mass properties, loading- and velocity-conditions necessary. For specification of clump attributes and pebble properties, it requires appropriate "clump attribute" and "clump property" commands [ICG15]. This clump logic is used for the implementation of the parcels in subchapter 3.2.2. Figure 34 gives a closer look on the clump replication for generating parcels in the waterfall model.

6. General wall logic:

   A wall is a "*manifold surface composed of triangular facets*" [ICG15]. A triangular mesh of n facets ($\{F^{(i)}\}$; i=1,2,..,n) constructs a wall, each facet is a piece that is assembled of three edges ($\{E_k^{(i)}\}$; k=1...3) (see Figure 29). The three vertices ($\{V_k^{(i)}\}$; k=1...3) that are describing a facet have to be unique and they are oriented so that the normal ($n^{(i)}$) of the facet is defined by the right-hand rule. The perpendiculars (normal to each facet of the wall) are aligned consistently with neighbouring facets or those sharing a common edge or vertex (e.g., "*a point traversing directly above/below a faceted wall is above/below the facet closest to the traversal point except near wall boundaries*" [ICG15]).

$$n^{(i)} = \frac{\left(E_1^{(i)} \times E_2^{(i)}\right)}{\left\|E_1^{(i)} \times E_2^{(i)}\right\|}$$

The surface properties of a wall can be specified independently for each facet. Walls can translate and rotate (defined by {v,w}, the generalized velocity v and angular velocity, or spin w of the wall about the reference point). Wall motion does not obey the equations of motion. In case of deformation, then independent translational velocities can be applied to each vertex ($\{v^{(k)}\}_{k=1,2,...,n} \rightarrow$ these values are specified directly). Wall deformation must preserve the manifold nature of the wall. Figure 29 shows a depiction of a wall facet from above [ICG15].
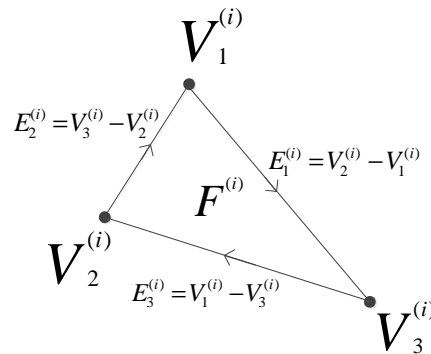
Figure 29: Depiction of a wall facet (viewed from above) [ICG15]

3.2.2 Implementation of the Waterfall Model

In order to assess the overall accuracy of a measure, it is necessary to generate a reference model. The reference model represents an ideal model with a target value. The comparison of the calculated characteristic number with the value of the reference model allows an assessment. If both values fit together, it will be an indicator that the parameters were set correctly. The reference model is created from reflections and therefore it presents potential errors, so steps are required to minimize the risk ([HEK05]; [PBF+06]).

The aim of the implemented simulation model is the computation of parcels' volume centres' after they fell down from a vertical gap of two subsequent belt conveyors (waterfall height = 0,45m). Figure 30 shows a 3D-view of the implemented waterfall model with descriptions of the individual component parts. The practical of this master thesis is focused on the motion behaviour of parcels during 3D-singulation. The implemented waterfall model is assembled with two rigid deflectors and control barriers on the lower belt conveyor. These components are in brackets because they do not directly affect the motion behaviour of parcels during singulation from 3D to 2D, but they illustrate the possible implementation from 3D- to 1D-singulation.
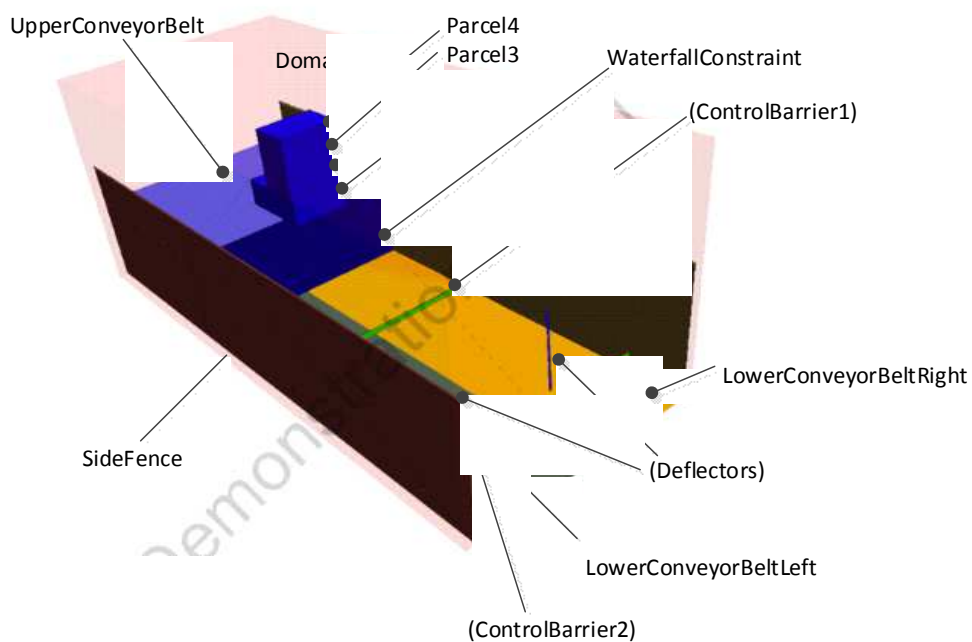
Figure 30: Waterfall model

Figure 31 outlines the fundamental properties of the "Base" for the waterfall scenario. This extract from PFC3D-code in appendix 8.2.1 defines disturbance variables, model domain and the contact model assignment table (cmat). The selection of simulation parameters is explained in chapter 3.3, the dimension of the domain depends on the required geometry and the cmat-command controls the assignment of the Hertz-model and their associated properties between "pebble-pebble" (parcel-parcel) and "pebble-facet" (parcel-ground).

```
title 'Base'


@Simparameter
[Poi = config(1,k1)]     ;Poisson's ratio Parcel

@SetDisturbanceVariables
[SP      = DisturbanceVariables(1,var1)]  ;Shear Modulus
[DP      = DisturbanceVariables(2,var2)]  ;Damping coefficient Parcel
[fric1   = DisturbanceVariables(3,var3)]  ;Friction Parcel-Parcel
[fric2   = DisturbanceVariables(4,var3)]  ;Friction Parcel-ConveyorBelt


domain condition destroy extent 0 [c1x+c2x] -0.05 1.25 @h 0.7


cmat default model hertz property hz_shear 1.0e10 hz_poiss 0.3 dp_mode 0 dp_nratio 0.1 dp_sratio 0.1 fric @fric2
cmat default type pebble-pebble property hz_shear @SP hz_poiss @Poi dp_mode 0 dp_nratio @DP dp_sratio @DP fric @fric1
cmat default type pebble-facet property hz_shear 1.0e10 hz_poiss 0.3 dp_mode 0 dp_nratio 0.1 dp_sratio 0.1 fric @fric2
```

Figure 31: Data file "Base" of PFC3D code

The parts "LowerConyeyorBeltLeft", "LowerConyeyorBeltRight", "UpperConyeorBelt" and "WaterfallConstraint" are created with the geometry polygon command. A list composed of edges, nodes and positions can be used for creation of a polygon. Figure 32 illustrates an example of a polygon generation, the wall "LowerConveyorBeltLeft" is implemented by four points. The variable c2x stands for the belt length of the upper conveyor and c1x for the length of the conveyor on the bottom. The bottom conveyor is divided into two polygons for simulating an split inclined belt conveyor, which pushes the parcels to the side fence. All four points of this polygon have the z-coordinate h which represents the fall height. Defined variables in the data file "Parameter" (appendix 8.2.2) can be called by the symbol @.

```
;Generation of LowerConveyorBeltLeft
wall generate id 1 name LowerConveyorBeltLeft polygon ...
            @c2x 0 @h ...
            @c2x 0.6 @h ...
            [c1x+c2x] 0 @h ...
            [c1x+c2x] 0.6 @h
```

Figure 32: Generation of a polygon

Figure 33 is a blueprint of a parcel generation. This example exhibits the implementation of the lowest parcel in the parcel tower with a cuboid shape within the domain 0 0.4 0 0.31 0.005 0.145, a volume of 0.4*0.31*0.14 (according Table 2: medium), a mass of eight kilograms and the resulting density (mass/density). By the creation of a clump from a variety of pebbles, the "clump template" command contains a surface description and visualisation properties. The "bubblepack ratio" characterises the ratio of the smallest to largest pebble in the clump, the "distance" defines the pebble distribution (value of 140 generates a pretty smooth surface) and the default "radfactor" of 1.05 limits the pebble overlapping with surrounding surfaces. Clump templates assume that parcels get an evenly distributed density and the inertia has to reflect this condition [ICG15].

```
;Generation of Parcels
geometry set Parcel_1
geometry generate group Parcel box 0 0.4 0 0.31 0.005 0.145
[vol1 = 0.4*0.31*0.14] ;Volume of Parcel_1
[mas1 = 8] ;Mass of Parcel_1
[den1 = mas1 / vol1] ;Density of Parcel_1
clump template create name Parcel_1 geometry Parcel_1 surfcalculate ...
    bubblepack ratio 0.005 distance 140 radfactor 1.05
```

Figure 33: Generation of parcels

Figure 34 exposes the creation of a clump from a template by the help of the "clump replicate" command. Prerequisite for the successful implementation of the waterfall model is that every replicated clump has to fall entirely within the predefined model domain; otherwise the simulation loop will be interrupted. Every parcel clump gets a continuously available "id" with associated density "@den*1to4*" from parcel generation in Figure 33. This "density" keyword avoids that the clumps get an unevenly distributed density. The keyword "position" sets all four parcel-clumps on their centre of gravity from which they can then

be extracted to their shape. The keyword "axis" specifies the z-axis as that axis about which to rotate the clumps. The first clump is aligned perpendicular to the x-axis ("angle 0"), the other three clumps are positioned transversely ("angle 90") to the first one. For avoiding wedging between clumps and the pairing clump-facet, the z-coordinates of all parcel-clumps were moved slightly upward to create minimal gaps in between.

```
clump replicate name Parcel_1 id 1 density @den1 position 0.92 0.7 0.075 axis 0 0 1 angle 0
clump replicate name Parcel_2 id 2 density @den2 position 1.01 0.7 0.1985 axis 0 0 1 angle 90
clump replicate name Parcel_3 id 3 density @den3 position 1.01 0.7 0.3045 axis 0 0 1 angle 90
clump replicate name Parcel_4 id 4 density @den4 position 1.01 0.7 0.4105 axis 0 0 1 angle 90
```

Figure 34: Clump replication for parcels

For displaying the individual positions of all four investigated parcels, the implementation of the "Finder" is necessary (see Figure 35). Each position provides the x-, y- and z-coordinate of every single parcel and includes additional information about the velocity of each clump. For finding a clump, the syntax "cp=clump.find(id)" must be used whereby "cp" is returning the clump pointer and "id" is arguing clump identification. The syntax for finding positions and velocities work identically. The statement "whilestepping" causes the execution of the loop; the statement "end" terminates the loop.

```
define Finder
  whilestepping

  c1 = clump.find(1)
  pos1 = clump.pos(c1)
  vel1 = clump.vel(c1)

  c2 = clump.find(2)
  pos2 = clump.pos(c2)
  vel2 = clump.vel(c2)

  c3 = clump.find(3)
  pos3 = clump.pos(c3)
  vel3 = clump.vel(c3)

  c4 = clump.find(4)
  pos4 = clump.pos(c4)
  vel4 = clump.vel(c4)

  end

  @Finder
```

Figure 35: Definition of finder

For the computation from all twelve parcel coordinates of additional 64 test runs in attached Table 19 (see appendix 8.2.6), the implementation of the output file is required (see Figure 36). The output file lists the simulation run number, the three most important influencing factors (Shear Modulus, coefficients of friction between parcel-parcel and parcel-ground; see DoE design in subchapter 4.1.1) and the four simulated coordinates from each of the four examined parcel centres (see Table 19). The real time of one singulation loop is set to 1.8 seconds (see program code: parameter in appendix 8.2.2); PFC3D has required approximately seven minutes for computing one simulation run.

```
define Final

    nrunNumber = string(runNumber)
    Filename = string('Output'+'.txt')


    OUT_DisturbanceVariables_runNumber  = string(runNumber)
    OUT_DisturbanceVariables_SP         = string(SP)
    OUT_DisturbanceVariables_DP         = string(DP)
    OUT_DisturbanceVariables_fric1      = string(fric1)
    OUT_DisturbanceVariables_fric2      = string(fric2)
    OUT_Time                            = string(tcurrent)
    OUT_Clump1_PosX                     = string(comp(pos1,1))
    OUT_Clump1_PosY                     = string(comp(pos1,2))
    OUT_Clump1_PosZ                     = string(comp(pos1,3))
    OUT_Clump2_PosX                     = string(comp(pos2,1))
    OUT_Clump2_PosY                     = string(comp(pos2,2))
    OUT_Clump2_PosZ                     = string(comp(pos2,3))
    OUT_Clump3_PosX                     = string(comp(pos3,1))
    OUT_Clump3_PosY                     = string(comp(pos3,2))
    OUT_Clump3_PosZ                     = string(comp(pos3,3))
    OUT_Clump4_PosX                     = string(comp(pos4,1))
    OUT_Clump4_PosY                     = string(comp(pos4,2))
    OUT_Clump4_PosZ                     = string(comp(pos4,3))
```

Figure 36: Output definition

3.3   Design of Experiments (DoE)

The DoE method has a comprehensive character because it is focused on the simultaneous analysis of several factors, this approach excludes that not only a favourite factor after another is examined. This statistical test setup is used for analysing complex problems with more factors on different levels. By using orthogonally fields (see chapter 4.1.1) it is possible to reduce the simulation effort. Instead of testing each factor individually, the DoE approach makes it possible to vary the factors with each other ([KLE13]; [SBH10]).

DoE investigates the effect of control variables under the influence of disturbance variables. This statistical approach has the objective to recognize effects of control parameters and to optimize the quality feature (target value). Figure 37 exhibits the parameter diagram of any DoE. If this qualitative system description contains fundamental errors, no experimental procedure leads to a repeatable solution and no statistician can adjust failures of this essential requirement. At first, it is essential selecting process factors for the study and determining objectives of an experiment [SBH10]:
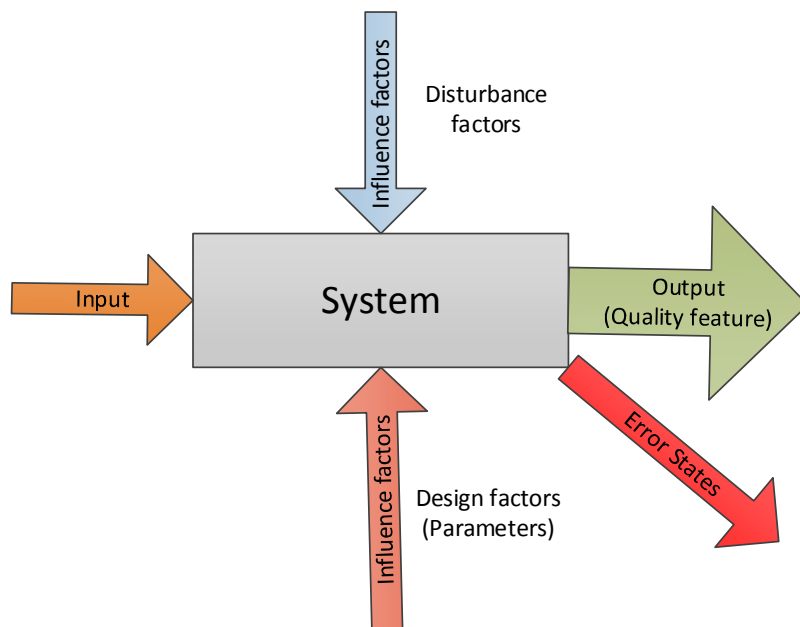
Figure 37: Parameter diagram [SBH10]

- **Influenceable parameters (control variables):** Influenceable factors can be machine settings, composition of its raw materials or process adjustments. For these parameters, the optimal setting is sought which makes the process robust against interference [SBH10]. Influencing factors are able to change target values; therefore, the step of problem analysis and identification of influencing factors takes a lot of time within a DoE.

- **Not modifiable parameters (disturbance variables):** Either these quantities cannot be affected or they are simply too expensive to ensure constant conditions (e.g. humidity, ambient temperatures). The target value and the process should be insensitive against these disturbances and the experimental procedure implies that disturbance variables have to vary [SBH10]. This step in DoE-procedure contains the parameter reduction, weighting and selection of influencing factors.

Figure 38 displays the three fundamental phases during DoE approach, each of them contain five points. Many of these points are applied on the waterfall scenario in the following subsections from 3.3.1 to 3.3.3 [SBH10].
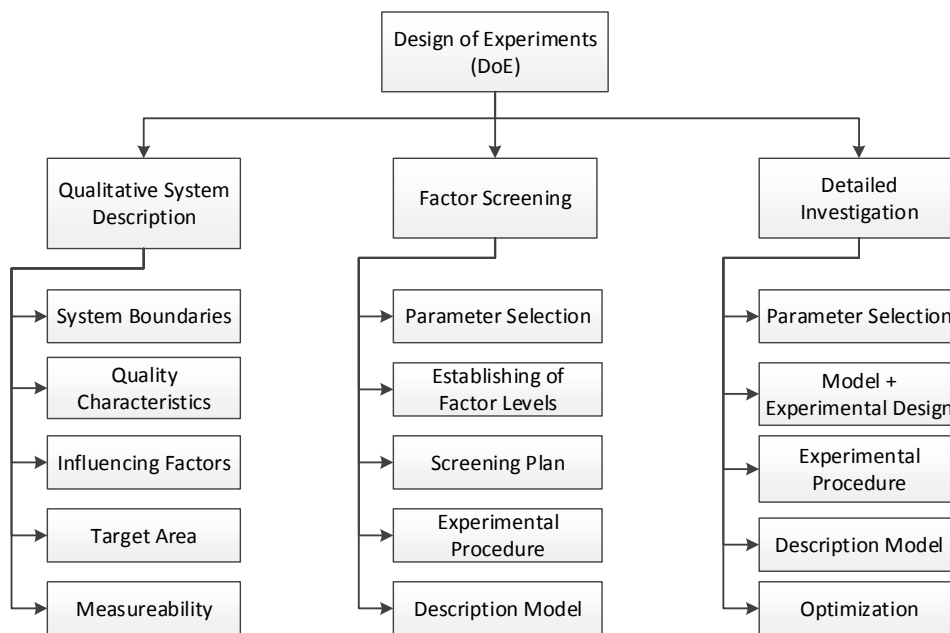
Figure 38: Three phases of the DoE-approach [SBH10]

Figure 39 illustrates the procedure of statistical experimental design that is applied to the waterfall model. This procedure gives an overview of the executed activities during DoE-approach. The different parameters undergo at the beginning a screening and then follows a deeper investigation of some chosen parameters. The procedure for preparation of the experimental design can be broken down into steps description of the initial situation, definition of the study objective, definition of the target and influence factors and determination of factor levels. If the final experimental design is on hand, the execution of the tests provides experimental results (PFC3D) and by means of statistical evaluation obeys an interpretation whether the desired examination target already achieved or whether another attempt planning step is necessary ([KLE13]; [WIE11]).
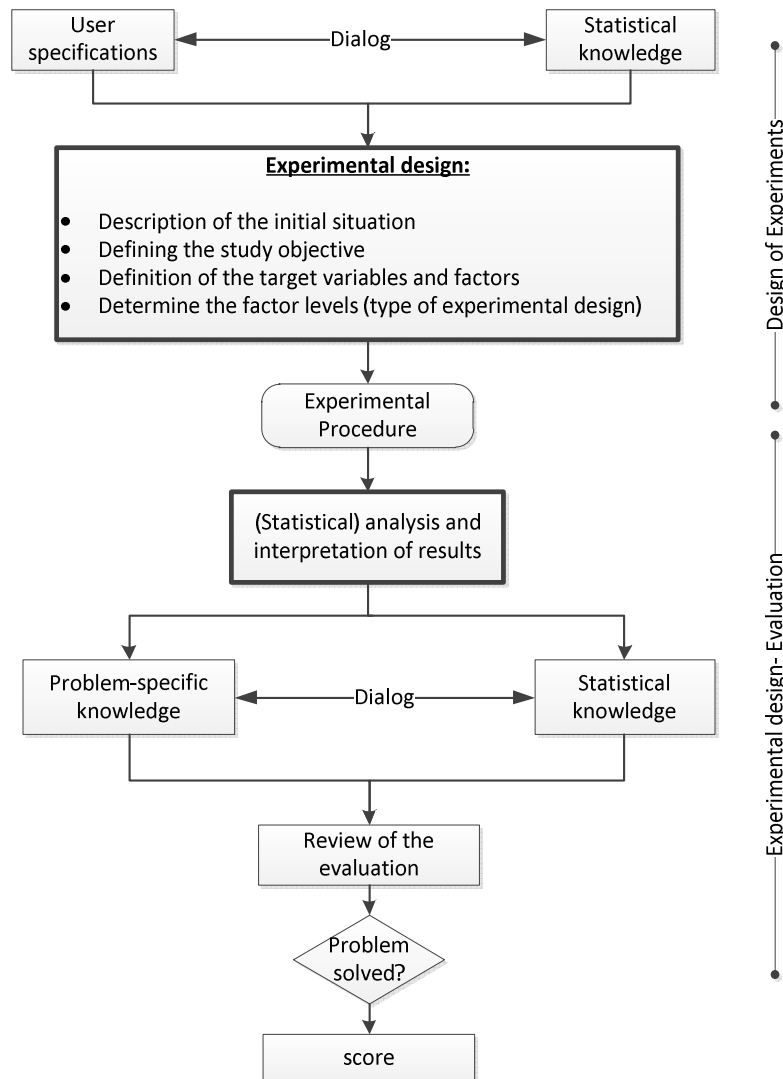
Figure 39: Experimental design structure [WIE11]

3.3.1 Qualitative System Description

The following points give a closer look on the qualitative system description for the implementation of the waterfall scenario.

1. Problem analysis, identification of influencing factors (3D-singulation): The parameter classification for the alignment procedure requires the definition of appropriate system boundaries. For the qualitative description of the singulation degree, it is necessary to implement a successful gaps counter. With the help of control rooms it should be possible to count the gaps between the packages. Following input parameters have to be considered for this model:

   - vertical gap between two subsequent belt conveyors (waterfall height) for singulation from 3D to 2D
   - coefficient of friction (corrugate cardboard, phenolic paper, steel) between the pairings parcel-parcel and parcel-ground
   - damping coefficient
   - stiffness coefficient
   - required time of singulation
   - conveying speed
   - time of singulation procedure (for one simulation run)
   - deflector angle for singulation from 2D to 1D
   - parcel dimensions (mass=4g...40kg, side length = 100mm...1.4m)
   - number of parcels in the parcel tower

   Figure 40 assigns these features to variable- and fixed-input parameters that influence the result "singulation degree". This result represents the quality characteristic of the "theoretical model", which cannot be so easily implemented in PFC3D. Therefore, it is necessary to introduce a substitute variable like an offset analysis of a "motion behaviour" that will be described in the following sub-item two.
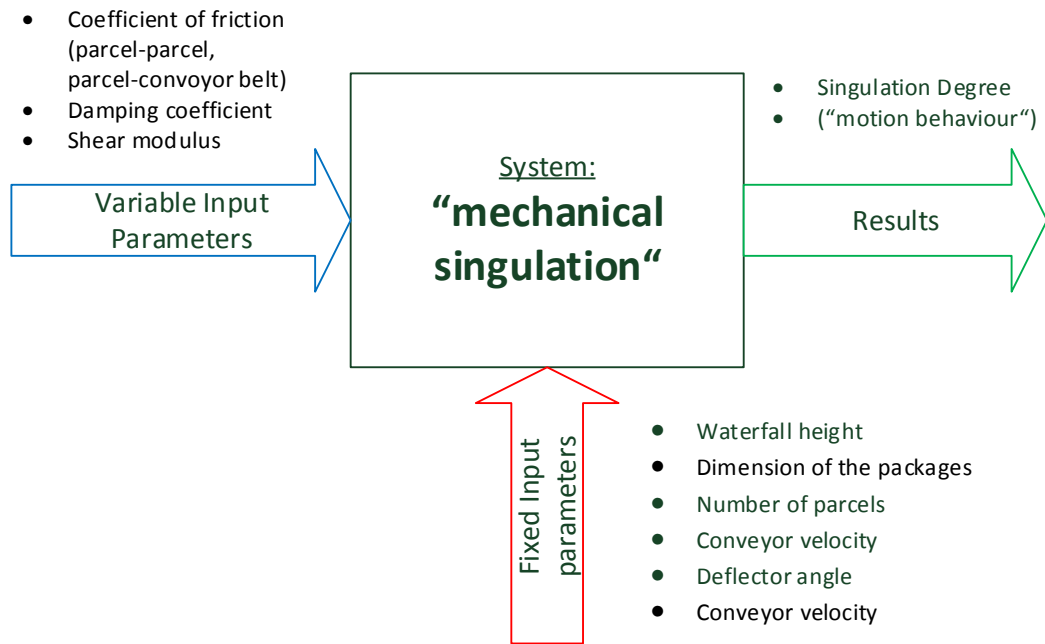
Figure 40: Schematic representation of the system "Singulation"

The settings of factors are called factor levels. Each factor is tested on at least two different levels. The steps are specified conditions or circumstances for the respective factors' setting. The effect of a factor depends on the setting of levels and the distances between the factor levels [SBH10].

2. Description of characteristic target value (quality characteristic):
Every system has one or several functions. The fulfilment of these functions is shown in measurable outcomes; positive outputs are also called quality characteristics. A system has been analysed through its quality characteristics. In practice, there is used more than one quality characteristic to cover all requirements. Different quality characteristics are noncritical and can be registered and evaluated independently [SBH10].
Quality characteristics are normally continuous dimensions. In some cases, the use of an auxiliary quantity is required for describing the digital system performance. In case of the waterfall scenario, the quality characteristic "position offset" represents the auxiliary quantity because the implementation of the singulation degree (SD) is too abstract and complex (see outlook 6.2).

Position offset analysis:

The objective of this approach is the description of a quality characteristic through computation of parcels' volume centres in PFC3D and comparison of simulated values with experimental investigation of real case waterfall scenario. Following formula determines an overall position offset from each parcel by adding each deviation in x-, y- and z- direction. Every single deviation in each direction is equal to the difference between simulation output and the specific average mean of the measurements from real attempts in Table 16.

$$offset := |\Delta \vec{s}|$$
$$= \sqrt{\left(pos_x^{sim} - pos_x^{real}\right)^2 + \left(pos_y^{sim} - pos_y^{real}\right)^2 + \left(pos_z^{sim} - pos_z^{real}\right)^2}$$

Table 17 (appendix) lists all offsets from each of the four parcels of the parcel tower that are calculated by the help of this formula.

3. Influencing factors due to model implementation:

This section gives a closer look on the target- and influencing parameters which impact the quality of the simulated model. Therefore, the use of a proper tool for quality control is necessary. Ishikawa (or Fishbone) diagrams are cause and effect diagrams that show the different causes of a specific event. This diagram type consists of one straight line that is attached to the problem statement (effect). The rest of the fishbone is made up of "bones", which are represented by several lines that coming out vertically from the main line. The logistic industry labels these branches according the "six Ms'" [KAN15].

Incorrect parameter settings from following four factors cause deviations of "position offset analysis" that compares the positions of parcels centres' between simulated and manually measured experiments (see Figure 41).

The implemented Hertz-model (see point three of chapter 3.2.1) uses these factors for describing the contact behaviour in the waterfall model. Therefore, these simulation-relevant values must be implemented proper-

ly so that the spatial motion behaviour of the parcels is reproduced as re-alistically as possible. The aim must be to keep the effect "Position Offset" as small as possible.
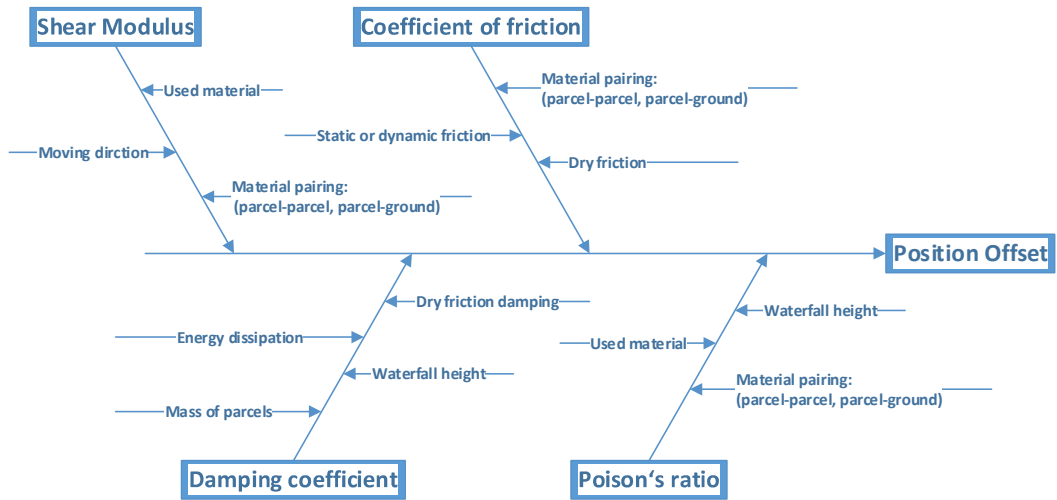
Figure 41: Ishikawa-diagram from "position offset" analyses

Table 6 summarizes all causes from effect "position offset", which have to be considered for building the simulation model. Especially the classification of the friction coefficient between parcel-parcel and parcel-ground must be considered for the waterfall model implementation in PFC3D.

Table 6: Screening of influencing factors for PFC3D implementation

Target Value	Factors
Position offset	Shear Modulus
	Coefficient of friction
	Damping coefficient
	Poisson's ratio

3.3.2 Factor Screening

This phase within a DoE-approach describes methods for parameter reduction, weighting and selection of influencing factors. Screening means vanning and thinning out from a broad range of factors, which have an impact on the characteristic target value of a system. The screening design refers to an experimental plan that is intended to catch the few significant factors from a pool of many potential ones. The primary purpose is to identify significant main effects rather than less important interaction effects. This procedure has the big advantage of minimizing the number of runs required in the procedure. The most frequently used DoE-designs are full- or fractional-factorial designs. The fractional factorial experimental design has the advantage of less experimental effort compared to full factorial experimental design [SBH10]. The following paragraphs give a closer look on the applied full factorial design for the waterfall scenario.

1. Parameter selection:

    This step contains the factor selection for the experimental procedure. Basic rule for this procedure is the selection of favourites from a large list of relevant factors and not to choose the first available factors. For the statistical DoE a rough classification of parameters in two assemblies is enough: factors, which are tested and remaining parameters, that are observed and kept constant. Factors have to be adjusted specifically and repeatable. It has to be guaranteed, that diverse combinations in experimental designs do not exclude each other [SBH10]. Closer definitions of the terms parameter and factor are listed in following two paragraphs:

    a. Parameter: The quantity of all inputs is called parameter. Even if it is possible to analyse just a few number of inputs at the beginning, it is advisable to create a complete listing of parameters right from the start for fixing all priorities and supporting the following test runs. This consideration of possible influencing parameters was carried out in the system "singulation" (see Figure 40) and in the parameter screening due to model implementation. The variety

of recognised parameters cannot be implemented entirely into the simulated waterfall model. Therefore, the less important parameters have to be screened out. That affects especially the damping coefficient and the Poisson ratio; both parameters could be considered as constant when they are set to a reasonable level. If a parcel is dropped to the ground, it does not jump back to its original height (energy dissipation). This effect allows the conclusion that a sensibly high setting of damping coefficient (DP = 0.9) minimises interactions of this parameter on the system (see program code in appendix 8.2.2). The Poisson ratio can be regarded as negligibly small in the implemented waterfall model (see Table 7) [KLE13].

b. Factors: The parameters that are included in the experimental design are called factors and represent a selected subset. It is obvious to choose factors, which have measurable effects on the system. In case of doubt it is advisable to test a bigger number of factors. Preliminary studies in PFC3D (e.g. observation of a parcel that falls from a vertical gap and hits the ground) has shown that Shear Modulus and the coefficients of friction between parcel-parcel and parcel-ground have the largest impact on the quality characteristic "position offset" in the waterfall scenario. The value ranges of these three influencing factors have to be established within borders, where simulated and measured parcel volume centres correlate with each other. This requirement needs the definition of factor levels and the number of adjustment levels in the experimental design that will be mentioned in the next points [KLE13].

2. Screening plan:

In full factorial designs, the factors are examined on at least two factor levels, which are referred with the normalized values plus/minus one. In the waterfall experiment, all factor levels of the various factors (factor A = Shear Modulus, factor B = coefficient of friction between parcel-parcel, factor C = coefficient of friction between parcel-ground) are combined and

that leads to 4^3 individual experiments (64 simulation runs) if the investigation starts with three factors and four factor levels. The advantage of this experimental design is that all factor effects and interactions can be estimated independently. The disadvantage is that the number of investigated factors of the test scope increases strongly. Full factorial designs are preferably used if there is no prior knowledge of the products or processes which are to optimize and the dependencies of the factors are mutually unclear. Usually two factor levels are used for a linear full factorial design and three for a cubic one. Figure 42 constitutes the cube for the quartic experimental design with three factors whereby the green balls represent the resulting 64 simulation runs [KLE13].
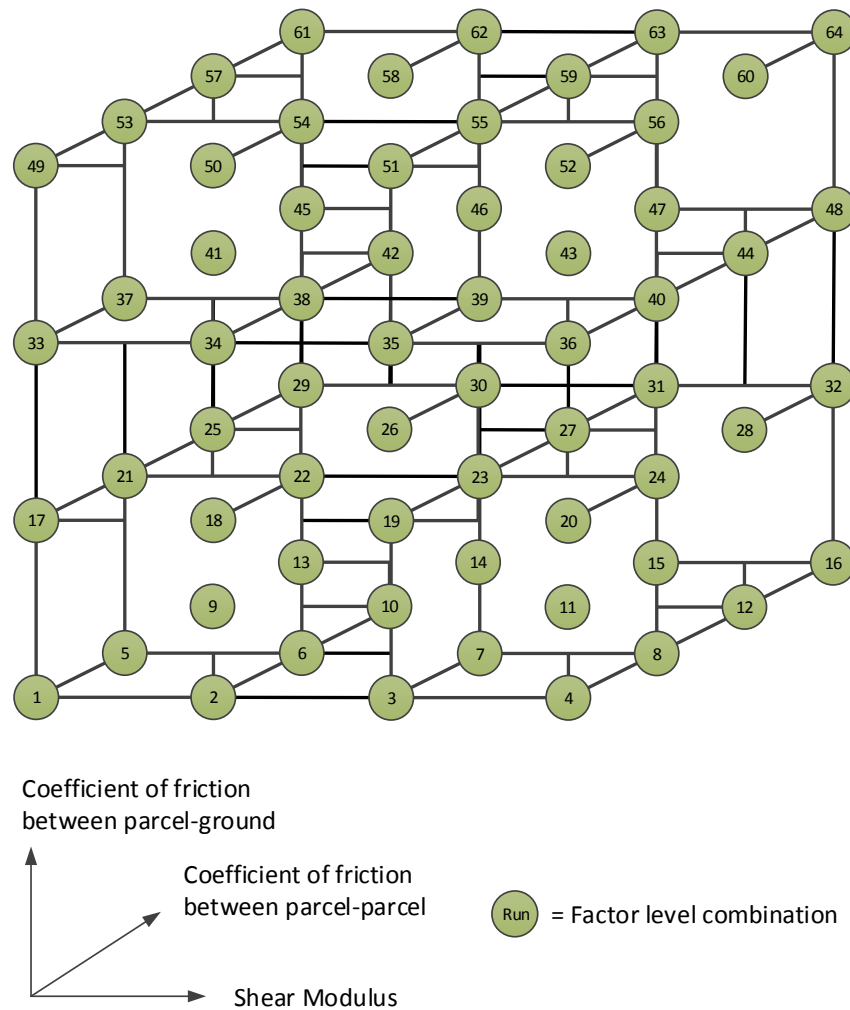
Figure 42: Full factorial design for three factors

3. Establishing of factor levels:

For DoE-preparation, the allocation of adjustment levels for influencing factors is required. Every factor must be tested on at least two levels. The levels are determined states or issues for the particular factor adjustment. The effect is depending on the level interval. A small interval is attended by small effect. At the beginning, big level intervals are better and variation of many factors can cause great changes for the system. Every factor should be set within realistic ranges of values [SBH10].

For the investigation of parcel singulation processes, it is necessary to determine the material characteristics of cardboard and the behaviour in combination to the material of the used ground (wood). The Shear Modulus G (hz_shear) for cardboard is only a fraction compared to this material constant of wood. Table 7 lists the values for both materials [POH08].

Table 7: Constraints of values for simulation in PFC3D [POH08]

Material Properties	Cardboard	Wood	Unit
Shear Modulus	90	800	[N/mm^2]
Poisson's ratio	~0	~0	[-]
Coefficient of sliding friction: parcel-ground parcel-parcel	0.2…0.4	0.2…0.4	[-]

These values represent guiding values, however, it is quite common for simulations using different values [PBF+06]. Values for cardboard are certainly too low, because the parcel box was filled with wood pellets. This circumstance leads to the assumption that the values for the influencing factor levels have to be fixed somewhere between the guiding values for cardboard and wood. The quality of the factor levels selection determines later the matching of simulated and manually measured volume centres from all four parcels in the parcel tower.

Figure 43 outlines the parameter implementation from PFC3D code in appendix 8.2.2. Respectively 16 simulation runs on each of the four factor

levels according to each of the three determined influencing factors are examined for the DoE investigation. That leads in total to 64 simulation runs which must be computed in PFC3D. The exact experimental design is listed in Table 10 in chapter 4.1.1. A closer look on the experimental design clarifies the definition of three variables ("DisturbanceVariables") and the setting of three variables on four factor levels ("SetDisturbance-Variables") that causes a four by four matrix (3, 4).

```
[DP = 0.9] ;Damping Coefficient


;DisturbanceVariables
[var1 = 1] ;Shear Modulus
[var2 = 1] ;Coefficient of friction between parcel-parcel
[var3 = 1] ;Coefficient of friction between parcel-ground


define SetDisturbanceVariables
array DisturbanceVariables(3,4)

;Shear Modulus
DisturbanceVariables(1,1) = 1e9
DisturbanceVariables(1,2) = 5e9
DisturbanceVariables(1,3) = 1e10
DisturbanceVariables(1,4) = 5e10

;Coefficient of friction between parcel-parcel
DisturbanceVariables(2,1) = 0.2
DisturbanceVariables(2,2) = 0.3
DisturbanceVariables(2,3) = 0.4
DisturbanceVariables(2,4) = 0.5

;Coefficient of friction between parcel-ground
DisturbanceVariables(3,1) = 0.4
DisturbanceVariables(3,2) = 0.7
DisturbanceVariables(3,3) = 1.0
DisturbanceVariables(3,4) = 1.3

end
```

Figure 43: Implementation of factor levels in PFC3D

4. Description model:

Main effect and interaction quantify the impact of the factors to the quality characteristic. The result is an equation which does not explain the underlying physical phenomenon but quantifies the correlations. A linear describing model with three factors could be [SBH10]:

$$y = c_0 + c_1 c_x + c_2 x_2 + c_3 x_3 + c_{12} x_1 x_2 + c_{13} x_1 x_3 + c_{23} x_2 x_3 + \varepsilon$$

It gives for every combination of input x_1, x_2 and x_3 an approximate value of the quality characteristic y. The variables $c_0 \ldots c_{23}$ are absolute terms in the model, the deviation ε is small in an appropriate model, compared to the variation of quality characteristic. For an optional number of factors yields the equation for the specification model analogue [SBH10].

$$y = c_0 + \sum_{i=1}^{n_f} c_i x_i + \sum_{i=1}^{n_f-1} \sum_{j=i+1}^{n_f} c_{ij} x_i x_j + \varepsilon$$

The number of model constants rises with each factor at the amount of factors. The summation of all factors results the total number of model constants [SBH10].

$$n_m = 1 + \sum_{i=1}^{n_f} 1 \qquad \text{with} \qquad n_{mi} = n_{mi-1} + n_{f_i}$$

The linear description model is very useful, because it describes a huge number of factors in a simple way. If the step sizes between the levels are not too big, the linearization shows good results [SBH10].

3.3.3 Detailed Investigation and Evaluation

The evaluation of parameters is executed through the analysis of relationships, which are based on correlations. If it is crucial to investigate the relationship between two metric (e.g. between disturbing variables and offsets) parameters, it's fundamental to calculate a correlation. A correlation consists of a correlation coefficient and a p-value. The correlation coefficient indicates the strength and direction of the relationship, it lies in the interval between minus and plus one. The p-value indicates whether the correlation coefficient is significantly different from zero, so if there is a significant relationship. In most cases, p values less than five per cent (0.05) are designated as statistically significant. There are various correlation coefficients, which are used at different data. In this study, the Pearson- and Spearman- correlation coefficient are discussed more in detail ([HEK05]; [KEL13]):

1. The Pearson correlation coefficient r is a dimensionless measure of the degree of linear correlation between two minimum interval scaled features. It can take values between minus and plus one and is applicable only for normally distributed data. At a value of plus one (or minus one), there is a completely positive (or negative) linear relationship between the observed characteristics. If the correlation coefficient has a value of zero, two characteristics are totally linear independent. Regardless, both characteristics can depend on each other in a nonlinear manner, so the correlation coefficient is not an appropriate measure for the pure stochastic interdependency of characteristics. This correlation coefficient is the arithmetic mean of the products of the standardized variable pairs. The standard deviations S_{xx}. S_{yy} and S_{xy} are the sums of squared deviations ([HEK05]; [KRÄ03]):

$$r = \frac{S_{xy}}{\sqrt{S_x S_y}}$$

$$\begin{cases} m_x = \dfrac{S_{xy}}{S_{xx}} \\ m_y = \dfrac{S_{xy}}{S_{yy}} \end{cases} \rightarrow m_x m_y = \dfrac{S_{xy}^2}{S_{xx}S_{yy}} \equiv r^2$$

$$S_{xy} = (x_1 - \bar{x})(y_1 - \bar{y}) + (x_2 - \bar{x})(y_2 - \bar{y}) + \cdots + (x_n - \bar{x})(y_n - \bar{y})$$

$$S_{xx} = (x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \cdots + (x_n - \bar{x})^2$$

$$S_{yy} = (y_1 - \bar{y})^2 + (y_2 - \bar{y})^2 + \cdots + (y_n - \bar{y})^2$$

2. The Spearman's rank correlation coefficient ρ is a parameter free measure of correlations, which means it measures how well an arbitrary monotonic function can describe the relationship between two variables without making any assumptions about the probability distribution of the involved variables. Unlike the Pearson correlation coefficient it does not require the assumption that the relationship between the variables is linear, this kind of coefficient is robust against outliers [HEK05].

$$\rho = 1 - \frac{6 \sum_i d_i^2}{n(n^2 - 1)}$$

$$d_i = rank(x_i) - rank(y_i)$$

Basically, the Spearman correlation differs from Pearson correlation only by conversion of values to ranks before the coefficients could be computed. This kind of analysis is not required for the waterfall model; therefore, the validation is based on Pearson correlation. A value close to minus one indicates a strong negative relationship. A value close to one indicates a strong positive relationship. No relationship exists when the value is close to zero. Table 8 lists a more detailed assessment of Pearson correlation coefficient [KRÄ03]. The data for the position offset analysis in the waterfall model are normally distributed (see chapter 5.4); therefore, this rating is applied to the Pearson correlation coefficient (see chapter 4.1.2). Thus, the relationship between the factors can be classified due to the colours that show the strength of a certain correlation.

Table 8: Rating of correlation coefficients [KRÄ03]

Correlation coefficients	Rating
$|r| < 0{,}2$	very low correlation
$0{,}2 \leq |r| < 0{,}5$	low correlation
$0{,}5 \leq |r| < 0{,}7$	medium correlation
$0{,}7 \leq |r| < 0{,}9$	high correlation
$0{,}9 \leq |r| \leq 1$	very high correlation

The smallest variation, i.e. the highest robustness of the process due to influences of variations of disturbing parameters is achieved when the control variables are provided on those steps, on which each variable causes the smallest standard deviation. The impact of a factor to the system is indicated through the effect. The effect means the difference between two arithmetic means, the arithmetic mean by the adjustment plus (+) and the arithmetic adjustment by the adjustment minus (-). The effect quantifies the median registered variation of the quality characteristic by the change of the factor adjustment from plus to minus. This procedure is called method of contrast. Four independent transitions happen for each factor [SBH10].

The effect for factor A (Shear Modulus) is calculated by:

$$E_A = \frac{y_2 + y_4 + y_6 + y_8}{4} - \frac{y_1 + y_3 + y_5 + y_7}{4}$$

For factor B ((coefficient of friction between parcel-parcel) the same experimental data is used, in another grouping:

$$E_B = \frac{y_3 + y_4 + y_7 + y_8}{4} - \frac{y_1 + y_2 + y_5 + y_6}{4}$$

The same results of the effect for factor C (coefficient of friction between parcel-ground):

$$E_C = \frac{y_5 + y_6 + y_7 + y_8}{4} - \frac{y_1 + y_2 + y_3 + y_3}{4}$$

The interaction of effects indicates the median changing of quality characteristics as a result of level variation. It does not preclude, that a dependency exists to the initial state. If the effect of a factor depends on the adjustment of another factor, there exists an interaction or an effect of interaction. To define an effect of a factor conceptually, it is also called main effect [SBH10].

The first two phases of the DoE approach in Figure 38 have been dealt with most of the sub-items from the third phase. Therefore, it will considered only the term "optimization" for the last phase that explains more or less the regression analysis for the experimental investigation of the waterfall scenario.

Optimization by linear regression:

It is not advisable the use complex simulation models for analysis of technical systems because they require enormous computation capacity. Meta-models offer significant shorter calculating periods which is particularly useful in this case and they approximate with sufficiently exact results the complex simulation model. Meta-models are made of known data points and the more data points are used, the more precise the meta-model works. The meta-models are built up of data which were taken out of a test field that has been designed for computer experiments. These test fields are constructed in a way, that the generated data supply a maximum amount of information with minimum number of trials. This enables them to create enough information to display linear as well as complex correlations between input variable (factor) of a model and the output variable which has to be analysed ([SBH10]; [HEK05]).

Local and global procedures are distinguished. Local procedures, like "*Kriging*" approximate the searched functional value y through an unknown factor combination x_0 via data points in a predefined area around x_0. Global procedures like artificial neural networks build up a meta-model which bases on all data points.

For meta-model generation, algorithms are used which do not need any explicit specifications of the expected correlations and are able to assimilate to the complexity of the system [HEK05].

For a variety of analysis and development tasks linear regression is used to produce meta-models. Siebertz argues in his book that linear regression provides sufficiently exact meta-models with minimum computing time, when all fundamental correlations between input and output variable are known [SBH10].

The general linear regression model has following form:

$$y_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + \cdots + b_{n_f} x_{in_f} + \varepsilon_i$$

The output y is the variable that has to be analysed, $x_{i1} \dots x_{in_f}$ are independent factors which do influence y. $b_1 \dots b_{n_f}$ are unknown constants which are determined by the measured data to adapt the linear regression model. The term ε is a random error which represents the part of the described system that can´t be explained by the linear regression model. The expected value of ε is above all n_r observances (data points) is zero $(\varepsilon|x) = 0$. Furthermore all ε_i of the data points $1, \dots, n_r$ are independently from each other and have an unknown variance $Var(\varepsilon|x) = \sigma^2$ [SBH10].

In general the linear regression model is represented like this:

$$y_i = \sum_{j=0}^{n_f} b_j x_{ij} + \varepsilon_i \, with \, x_{i0} \equiv 1$$

For determining the constants $b_0, \dots, b_{n_f}$ the method of least squares must be applied. This method minimises the sum of the squared deviations between the veritable data point y_i and the prediction of the linear regression model $\hat{y}_i$ [SBH10]:

$$S(b) = \sum_{i=1}^{n_r} \left(y_i - \sum_{j=1}^{n_f} x_{ij} b_j \right)^2$$

$$S(b) = (y - Xb)^{'}(y - Xb)$$

The derivative of $S(b)$ with respect to b is:

$$X^{'}y = X^{'}Xb$$

Is $X^{'}X$ invertible the coefficients b can be estimated:

$$\hat{b} = \left(X^{'}X\right)^{-1}X^{'}y$$

The variance of ε can be determined as follows:

$$\hat{\delta}^2 = \frac{\sum_{i=1}^{n_r} y_i - \hat{y}_i}{n_r - n_f - 1} = \frac{\sum_{i=1}^{n_r}\left(y_i - \sum_{j=0}^{n_f} x_{ij}\hat{b}_j\right)}{n_r - n_f - 1}$$

For the verification of the validity and prediction accuracy of a linear regression model, the divergences between measured data points and the predictions of the linear regression model are analysed, so called residual: $r_i = y_i - \hat{y}_i$ [SBH10].

The residuals have to evenly vary over all data points and have to have adequate minimal absolute values for analysis. Beside the choice of used factors and meaningful variables as well as the used kind of model, the verification of the produced meta-model is one of the most important steps in generation of meta-models. The verification can be achieved via the approximation accuracy of additional data points which were not used to create the meta-model or with the help of cross-validation. This procedure leaves out data points for using them later on for verification ([SBH10]; [HEK05]).

3.4 Sensitivity Analysis

Mathematical models of real systems (e.g. medical, physical) are usually based to a variety of complex, non-linear and coupled equation systems. A prerequisite for a meaningful analysis of these equations is a comprehensive understanding of the influence of the variance of the input variables x on the variance of the observed output variables y. The term sensitivity analysis investigates the relationship between the variance of the input parameters $x = (x_1,...,x_{fn})$ and the variance of the output parameters y, basically it can be distinguished into following three areas [SBH10]:

- **Factor Screening** determines the qualitative impact of input variables on an output variable. This procedure is mainly used to distinguish between significant and non-significant factors, whereby no quantitative characteristic numbers are determined. For the practice in the industry is only a qualitative comparison of different factors relevant which makes a deeper consideration of this range irrelevant [SBH10].

- **Local Sensitivity Analysis** examines the influence of factors for a given function value of the output variable y (for example the local optimum). The examination checks basically how small changes in the factor settings affect the output variables. With this method it is possible to perform stability analysis (robustness) for selected factor combinations [SBH10].

- **Global Sensitivity Analysis** determines the influence of factors in variation throughout their domain. This method helps to gain a better understanding of the different factors in a model and to compare these with each other simultaneously. Figure 44 illustrates the basic procedure of the global sensitivity analysis [SBH10].
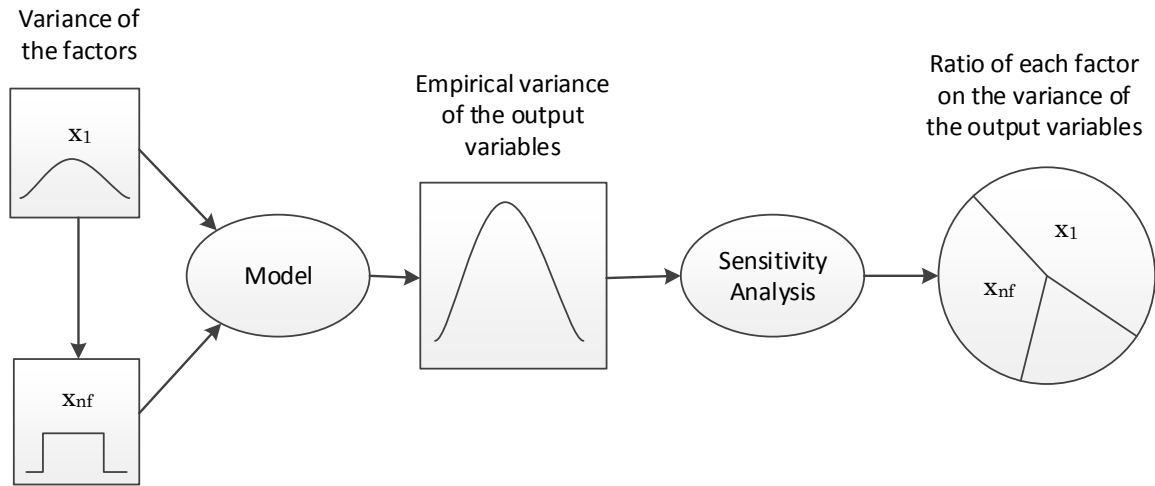
Figure 44: Global sensitivity analysis [SBH10]

Various factors (x_1,...,x_{fn}) have equal or different distributions, depending on the used deterministic model, variances of the input factors affect the resulting empirical variance of the output variable y. The global sensitivity analysis determines the ratio of each input factor x_j on the output variable y. Thus, a comparison of the significance of various factors for the output variable y is possible. The waterfall scenario will be examined with this kind of assessment. The three examined influencing factors are tested for their influence on the output variable "position offset" between measured and simulated parcel centres [SBH10].

3.5 Artificial Neural Networks

Simulation of parcel singulation processes present a cheap option in improving consisting conveying equipment compared to conventional test stands [FWL+15]. The simulation of complex singulation processes also requires high computation times. Therefore, the application of a forecasting tool is required that analyses existing simulation models from specific singulation scenarios and predicts probable outputs from input data sets which were not explicitly tested on those factor levels.

The Artificial Neural Network (ANN) approach is applied for the waterfall model with the target of forecasting parcel offsets when the levels of disturbance variables are not at the same factor levels as they were simulated. The simulat-

ed data is used as training data set for the ANN for identifying relationships between input (Shear Modulus, Coefficients of friction) and output variables (position offsets from parcels). By weighing of the different input parameters it shall be feasible to conclude on parcels' volume centres' even disturbing parameters are not set on their defined factor levels.

An ANN is assembled from biological nervous systems that are performing in parallel. This biological nervous system builds the basic principle for neurons, which largely determine the network function. By modifying and adapting of values from the connections (weights) between these artificial elements, it is possible to train an ANN in an appropriate manner to perform a particular function. By comparison of a sufficient quantity of input/target pairs, it is attainable to train the ANN until the network output matches the target. The process of training neural networks is processed by tuning the values of weights and biases until the network performance reaches an optimum [DB04].

Figure 45 illustrates this procedure of comparison between output and target, the main challenge of this approach is the determination of a sufficiently large data set for ensuring an adequate training [DB04].
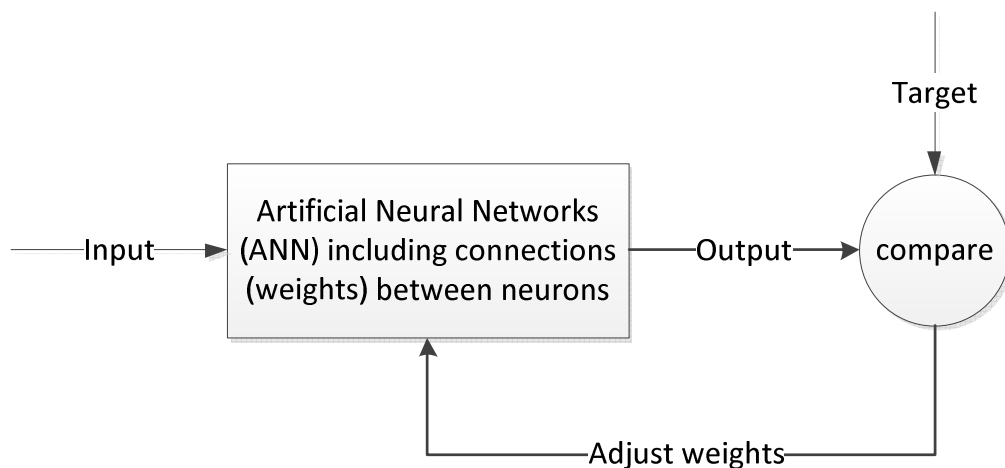
Figure 45: Basic structure of Artificial Neural Networks [DB04]

3.5.1 Implementation of Neural Networks in Matlab

The work flow for the neural network design process has seven primary steps. These steps include the application of ANN to the waterfall model and their implementation:

1. Data collection: Data for function fitting problems are set up for a neural network by organizing the data into two matrices, the network input matrix p and the target output matrix t (see appendix 8.2.6) [HHD15].

2. Network creation: The next step includes the creation of an ANN that learns to forecast parcel offsets between simulated and manually measured parcel centres'. Figure 46 displays the data selection for the ANN by the assignment of matrices to the Neural Fitting Tool. The input matrix "InputFactors" consists of 64 samples of three elements (disturbance factors) that are listed in Table 18 in appendix 8.2.6. The target matrix "TargetsOffsetsRelative" is a 64x12 matrix that is representing static data for 64 samples of twelve elements (x-; y- and z-coordinates of parcel centres' from each of the four parcels) that are listed in Table 19.
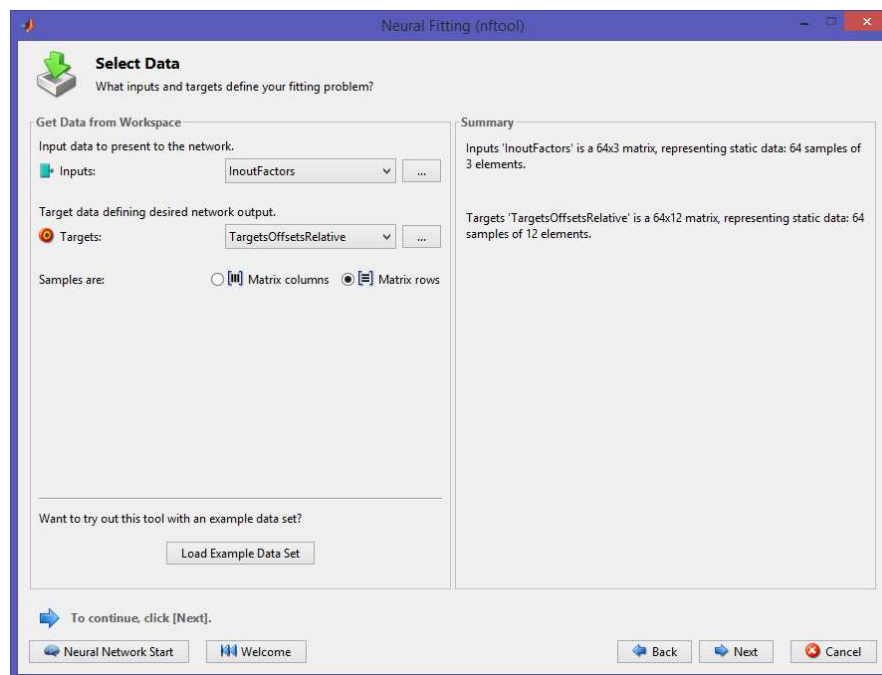
Figure 46: Data selection for Neural Fitting Tool

Figure 47 illustrates the network architecture for the ANN. For this fitting approach, the network is assembled of two feed-forwarded layers with ten neurons in the hidden layer [HHD15]. If the number of neurons in the hidden layer increases, it requires more computation and it is more likely to produce over fitting. Chapter 4.2 demonstrates that ten neurons in the hidden layer perform an appropriate network performance. Therefore, no adjustment of the neurons' number is required. Since the neural network starts with random initial weights, the results will differ slightly every time it is run [HHD15].
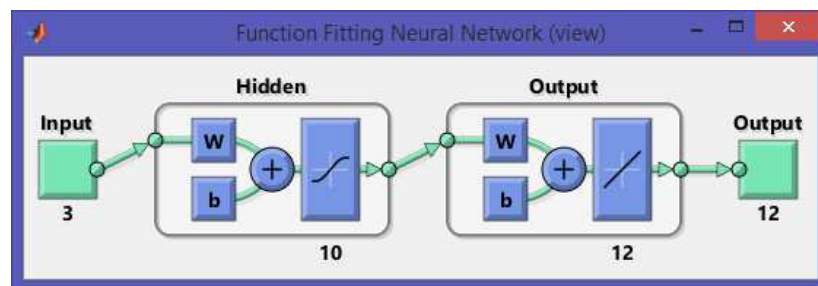
Figure 47: ANN-architecture

3. Network configuration: This step deals with the examination of input and target data. The network's input and output sizes are set during configuration in this way that inputs are matching targets. The chosen settings for processing inputs and outputs must be saved when the network has achieved its best performance. The configuration step is usually executed automatically when the training function is called [HHD15].

4. Weights- and biases-initialization: These properties define the network's modifiable parameters, its weight matrices and bias vectors. The ANN toolbox distinguishes between following three properties:

   a. **Net.IW** characterises the weight matrices of weights that go from network inputs to the layers. It is composed always of an N_l x N_i cell array, where N_l characterises the number of network layers and N_i the number of network inputs [HHD15].

b. **Net.LW** defines the weight matrices of weights that arrive to layers from other layers. It is composed always of an N_l x N_l cell array, whereby N_l is the number of network layers [HHD15].

c. **Net.b** describes the bias vectors for each layer with a bias. It is composed of an $N_l \times 1$ cell array, where N_l represents the number of network layers [HHD15].

5. Network training: When weights and biases from the network are initialized, the ANN is prepared for training. The common training procedure for multilayer networks starts with the division of the whole data set into three subsets. The first subset is the training set; it is used for this implementation step for computing the gradient and updating the network weights and biases. The gradient descent illustrates the simplest training algorithm [DB04]. The update of network weights and biases is processed in direction where the performance function decreases most rapidly. The following formula describes this training algorithm: x_k is a vector of current weights and biases, g_k is the current gradient and α_k is the learning rate. This equation is iterated until the network converges [HHD15]:

$$x_{k+1} = x_k - \alpha_k g_k$$

The multilayer feed forward network can be trained for function approximations like nonlinear regression. The default performance function for feed forward networks is represented by the mean square error (mse), the average squared error between the network's outputs (a) and the target values (t). It is defined in the following formula ([HHD15]; [DB04]):

$$F = mse = \frac{1}{N}\sum_{i=1}^{N}(e_i)^2 = \frac{1}{N}\sum_{i=1}^{N}(t_i - a_i)^2$$

6. Network validation: The second subset is the validation set. The error on the validation set is checked during training. The validation error usually

declines during the beginning phase of training, as well as the training set error. Nevertheless, when the ANN starts to overfit the data, the error on the validation set routinely begins to rise. The network weights and biases are retained at the minimum of the validation set error [HHD15].

7. Use of network: After step five and six (training and testing), the ANN can be used to compute the network response to any input. The third sub-set is adapted as test set, its error is not required during training, but it is needed for comparison of different models. It is also helpful to plot the test set error during the training process. A poor division of the data set causes the effect that "*the error in the test set reaches a minimum at a significantly different iteration number than the error in the validation set*" [HHD15]. ANN can be used to complement conventional statistical tools. If the experiments are set up properly, it is possible to minimise the potential for bias in the results. Figure 48 shows the percentages of the training-, validation- and testing-data set of the whole simulated data. 44 samples of 64 simulation runs will be used for training (70%) and respectively ten samples (15%) for validation and testing.
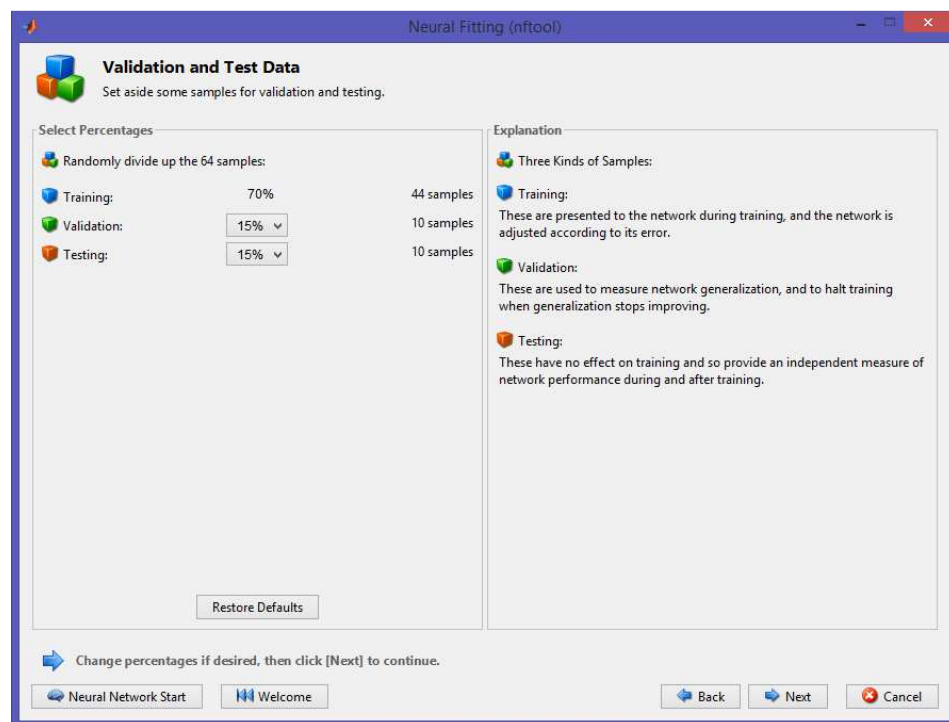
Figure 48: Neural Fitting Tool

3.5.2 Deploy Neural Network Simulink Diagrams

The ANN toolbox in Matlab provides a set of blocks which can be used to build neural networks in Simulink or for the generation of the Simulink version of any network that was created in Matlab. The function *"gensim(net,st)"* generates a block description of the created network, whereby the second argument of this function determines the sample time which is normally a positive real value. If a network has no delays associated with its input- and layer-weights, a value of minus one causes *"gensim"* to generate a network with continuous sampling [HHD15].

If the input signal of the constant input block x_1 changes, it is possible to simulate the system and to check the network's response in y_1. Figure 49 presents the block diagram of the Simulink editor for linear network.
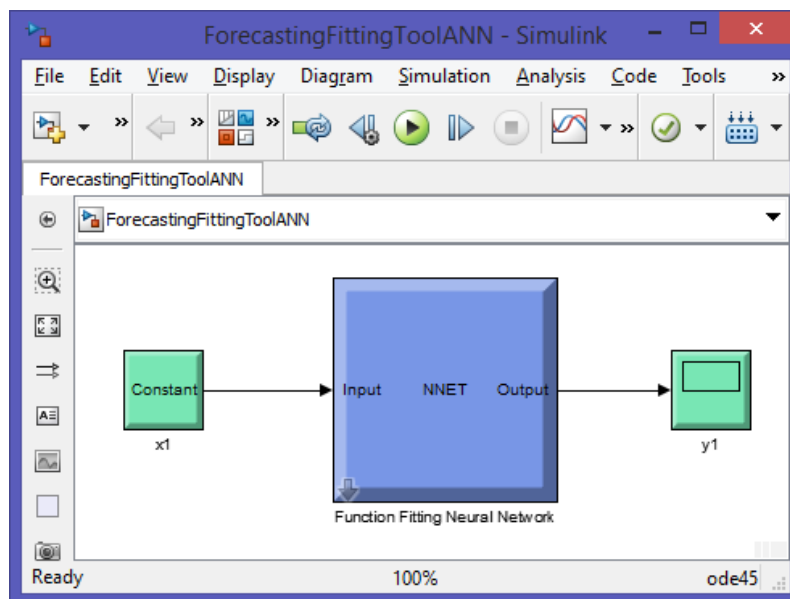
Figure 49: Simulink editor for linear network

Following sample demonstrates the definition of a set of inputs p and corresponding targets t. The first value of the input vector describes the Shear Modulus (SP), the second one the coefficient of friction between parcel-parcel (fric1) and the third one the coefficient of friction between parcel-ground (fric2). It is the first setting of the DoE-table (Table 18 in appendix 8.2.6), all disturbance factors are on the first factor level one (see Table 10 in chapter 4.1.1):

p= [5000000000; 0.4; 0.7]

The target vector provides the associated coordinates of parcels' positions (x, y and z) (see Table 19 in appendix 8.2.6):

t= [1.13699; 0. 741999; -0. 247852; 1. 36921; 0. 745024; -0. 339542;
    1. 47967; 0. 709061; -0.339542; 1.73106; 0.751486; -0.336399]

A double click on the constant x_1 block on the left in Figure 49 enables to test the network. Figure 50 shows the standard constant block of the Simulink editor which is used to enter the values of the inputs. For network testing, the inputs are set to values that were not simulated at these factor levels. The Shear Modulus is set on 8e10 N/mm², fric1 to 0.35 and fric2 to 0.9. These values are within the minima and maxima of the simulated factor levels of the disturbance variables, so the prognosis of parcels' positions is much more accurate.
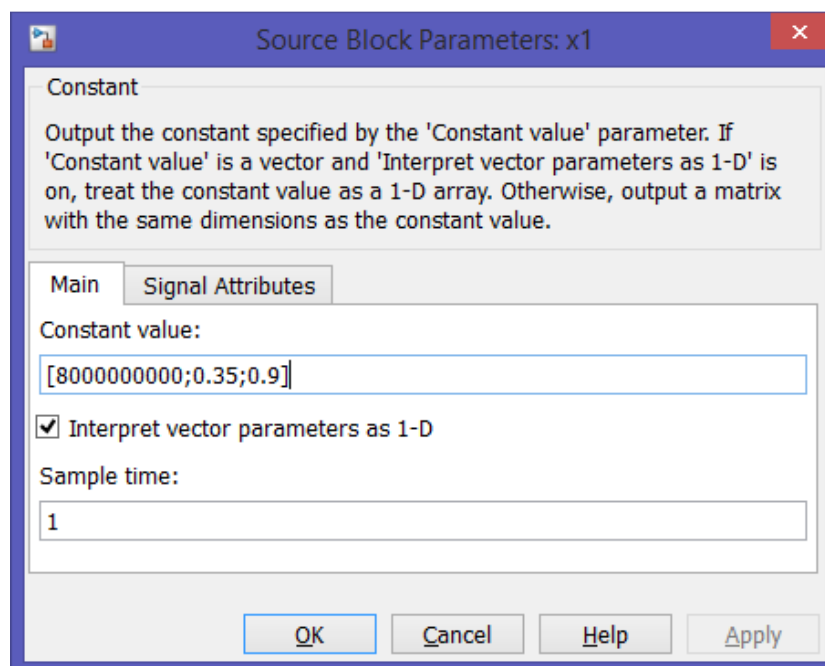
Figure 50: Source block of Simulink editor

By selecting the menu option Simulation → Run, Simulink takes some seconds to simulate the system. After completion of the simulation, a double click on the output y_1 block on the right in Figure 49 is mandatory to see the next display of network's response. Figure 51 exhibits the x-, y- and z-positions of all for parcels, which were calculated by ANN through weighing of the input factors (see point four of chapter 3.5.1). The results indicate a good quality; the z-coordinates are in the range of -0.3 meters, the y-coordinates in the range of 0.7 meters and the x-coordinates are represented by the top four lines (two red and two yellow). The x-coordinate from parcel one is estimated at 1.1 meters and from the smaller ones at 1.35 m, 1.65 m and 1.9 m.
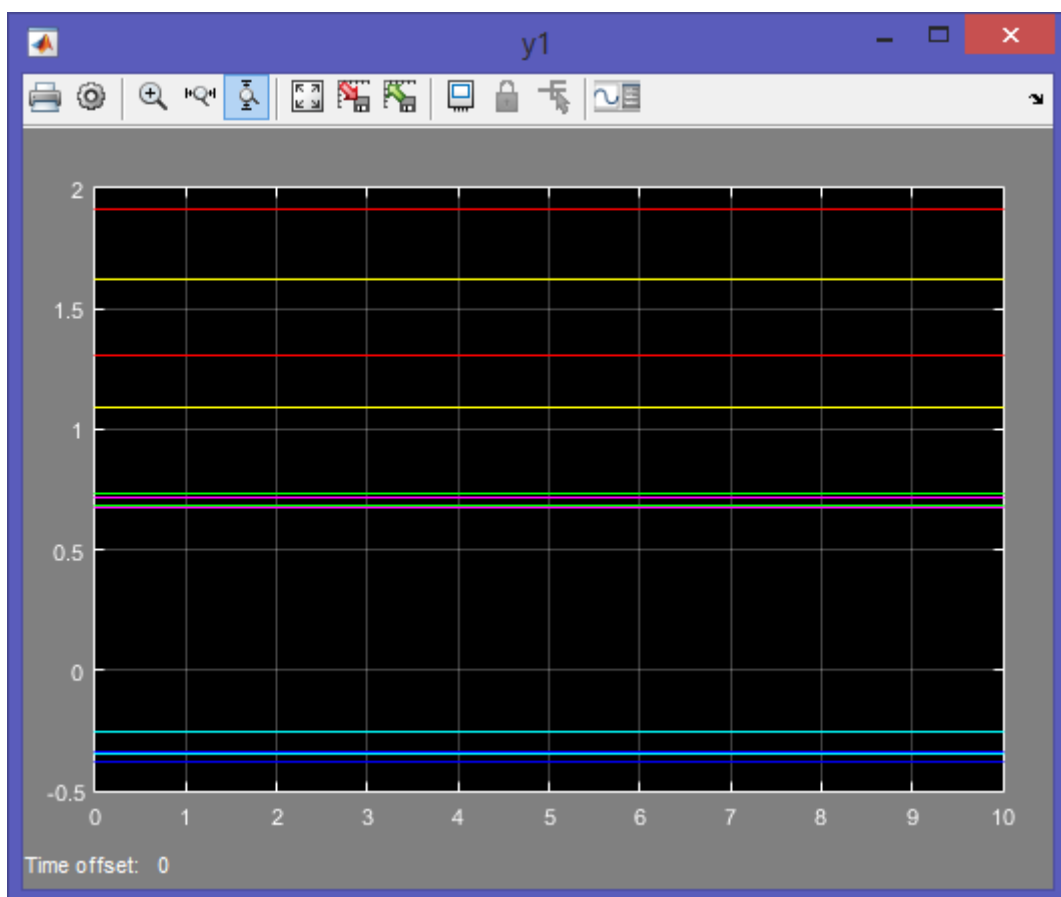
Figure 51: Output y_1 block of Simulink editor

4 Method of the Procedure

The direct comparison between computer based and physical experiments show some fundamentally different properties which are listed in Table 9 [SBH10]. If there is a unique relationship between input data (disturbance factors) and output data (quality criteria), a system or model is called deterministic. If a system provides for the same input data different output data (e.g. measurement scattering), the system is referred as stochastic. DEM-based simulation tools like PFC3D can be considered as deterministic due to avoidance of simulation loops with identical factor settings. Therefore, DEM-based simulation of parcels' spatial motion behaviour is an economical option for investigating large numbers of parcels during singulation processes.

Table 9: Comparison of computer and physical experiment [SBH10]

Computer based experiments	Physical based experiments
deterministically	stochastic
no measurement errors	measurement errors
high factor quantity	low factor quantity
flexible factor levelling	limited factor levelling
simple modification of factors	factor modification is difficult and time consuming

4.1   Results from Waterfall Scenario Examination

The following two subchapters 4.1.1 and 4.1.2 display the results from the conceptual modelling in section 3. The influencing factors that largely control the quality of the simulated position offset analysis from the parcels in the simulated waterfall model compared to the measured ones. This procedure is explained by the DoE-design in the first subchapter 4.1.1. The second subchapter 4.1.2 illustrates the achieved simulation quality by the help of a Pearson correlation plot that compares the simulated parcel centres' with measured ones'. The results of this subchapter provide whether the simulated values display a sufficient correlation with the measured ones. Chapter 4.2 outlines the results from ANN-application to the 3D-singulation procedure.

4.1.1   Full Factorial DoE-Design for Sensitivity Analysis

Orthogonal fields are tables for DoE-design with the instruction of parameter setting. Orthogonal arrays are based on the combination of each adjustment that was made with all other settings for creating statements with nearly statistical accuracy and reduced experimental effort [SBH10]. This kind of field is used for describing the waterfall model by setting disturbance factors on specific factor levels. For the simulation of 64 test runs, three factors are varied on four factor levels (1, 2, 3 and 4) (see chapter 3.3).

Table 10 depicts the DoE table for the sensitivity analysis of most important disturbing influences in the waterfall scenario. Shear Modulus and coefficients of friction between parcel-parcel and parcel-ground are tested via full factorial design. The compression of possible influencing factors to three disturbing influences leads to a minimization of the required simulation runs for the DoE approach. If another influencing factor (e.g. damping coefficient) is added to the DoE-design, the scope of simulation would be increase on 256 runs (4^4). The experimental effort could thus be minimized to an acceptable level.

Table 10: DoE-table

Run	Shear modulus	Coeff. of friction (parcel-parcel)	Coeff. of friction (parcel-ground)
1	1	1	1
2	2	1	1
3	3	1	1
4	4	1	1
5	1	2	1
6	2	2	1
7	3	2	1
8	4	2	1
9	1	3	1
10	2	3	1
11	3	3	1
12	4	3	1
13	1	4	1
14	2	4	1
15	3	4	1
16	4	4	1
17	1	1	2
18	2	1	2
19	3	1	2
20	4	1	2
21	1	2	2
22	2	2	2
23	3	2	2
24	4	2	2
25	1	3	2
26	2	3	2
27	3	3	2
28	4	3	2
29	1	4	2
30	2	4	2
31	3	4	2
32	4	4	2
33	1	1	3
34	2	1	3
35	3	1	3
36	4	1	3
37	1	2	3
38	2	2	3
39	3	2	3
40	4	2	3
41	1	3	3
42	2	3	3
43	3	3	3
44	4	3	3
45	1	4	3
46	2	4	3
47	3	4	3
48	4	4	3
49	1	1	4
50	2	1	4
51	3	1	4
52	4	1	4
53	1	2	4
54	2	2	4
55	3	2	4
56	4	2	4
57	1	3	4
58	2	3	4
59	3	3	4
60	4	3	4
61	1	4	4
62	2	4	4
63	3	4	4
64	4	4	4

4.1.2 Correlation Plot

The correlation plot in the following diagram (see Diagram 1) and validation table (see Table 11) visualize the results from sensitivity analysis in section 3.4 by the use of the DoE approach in section 3.3. The command "corrplot(x)" creates in Matlab a matrix that consists of a variety of single plots. These plots specify correlations between pairs of variables in x.

Diagram 1 displays the Pearson correlation plot of the selected disturbance variables (SP = Shear Modulus, fric1 = coefficient of friction between parcel-parcel, fric2 = coefficient of friction between parcel-ground) and the resulting parcel offsets (Offs.1, Offs.2, Offs3 and Offs.4) during singulation from 3D to 2D.

Along the main diagonals of the matrices are displayed histograms of the variables that provide a simple graphical view of the accumulated data from simulation runs including its dispersion and central tendency. The histograms along the diagonals in both correlation plots represent the easiest way for evaluating the distribution of all three influencing factors and the offsets of all four parcels. The correlation diagrams or scatter plots of variable pairs appear next to the main diagonal in the secondary diagonals. These graphical tools depict the influence that one factor has on another by displaying points that represent the observed value from one factor corresponding to the value of another factor. The slope of the single lines in the scatter plots, based on an ordinary least square regression, are equal to the displayed correlation coefficients in the upper left corner of each plot. The slope of the single lines in each correlation plot is statistically significant at the 95% confidence level (see chapter 5.4).

Both kinds of diagrams, histogram and scatter diagram, represent quality control tools that ensure analysis, improvement and verification of the whole DoE procedure.

The Pearson correlation coefficient is applicable only to normally distributed data, so this verification is provided in chapter 5.4. The correlation matrix shows high positive correlation coefficients (0.92 and 0.97) between the offsets (Offs.) of the smaller three parcels (see Figure 20). That indicates that there are strong linear dependencies between those parcels (according to Table 8). Shear Modulus (SP) and coefficient of friction between parcel-ground (fric2) have stronger linear dependencies to the offsets than the coefficient of friction between parcel-parcel (fric1). Table 11 exhibits a more accurate classification of the correlation coefficients that describe the linear correlations of disturbing factors on the target value "position offset".
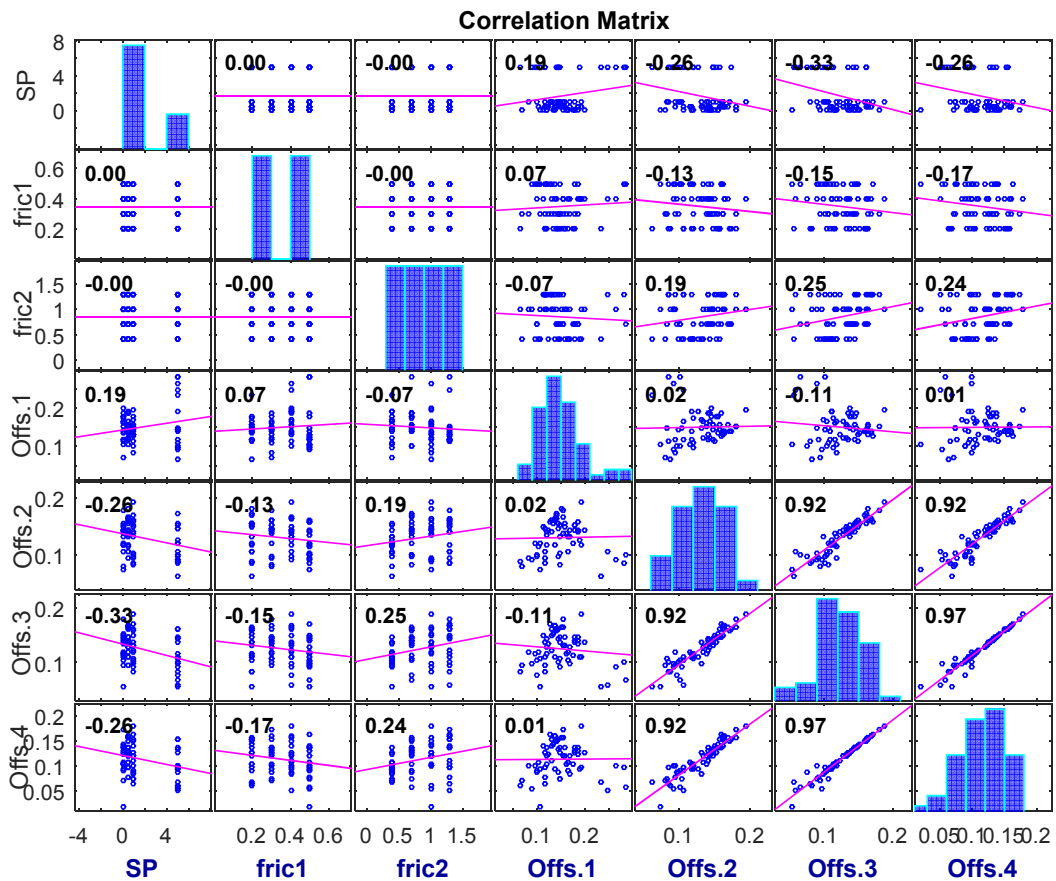
Diagram 1: Pearson correlation

Table 11 evaluates the correlation coefficients from Pearson correlation plot (see Diagram 1) with matching colours according Table 8. The position offsets from the smaller parcels that rest on the top of the medium one, have strong linear interdependencies (Pearson-Corr. > 0.9). The coefficient of friction between parcel-ground (green) has stronger linear interdependencies on the position offsets than the coefficient of friction between parcel-parcel (blue).

Table 11: Evaluation of Pearson correlation plot

x-Axis	y-Axis	Pearson-Corr.
Offset clump 3	Offset clump 4	0,97
Offset clump 2	Offset clump 3	0,92
Offset clump 2	Offset clump 4	0,92
Friction parcel-ground	Offset clump 3	0,25
Friction parcel-ground	Offset clump 4	0,24
Shear Modulus	Offset clump 1	0,19
Friction parcel-ground	Offset clump 2	0,19
Friction parcel-parcel	Offset clump 1	0,07
Offset clump 1	Offset clump 2	0,02
Offset clump 1	Offset clump 4	0,01
Shear Modulus	Friction parcel-parcel	0
Shear Modulus	Friction parcel-ground	0
Friction parcel-parcel	Friction parcel-ground	0
Friction parcel-parcel	Offset clump 1	-0,07
Offset clump 1	Offset clump 3	-0,11
Friction parcel-parcel	Offset clump 2	-0,13
Friction parcel-parcel	Offset clump 3	-0,15
Friction parcel-parcel	Offset clump 4	-0,17
Shear Modulus	Offset clump 4	-0,26
Shear Modulus	Offset clump 2	-0,26
Shear Modulus	Offset clump 3	-0,33

4.2   Artificial Neuronal Network Plots

Figure 52 provides in the training window four plots: performance, training state, error histogram and regression. The performance plot illustrates the value of the performance function versus the iteration number. This window shows training, validation and test performance plots. The training state plot demonstrates the progress of other training variables like gradient magnitude, number of validation checks, etc. For analysing the ANN the error histogram- and regression-plot are used because both plots validate the network performance. The error histogram plot shows the distribution of the network errors, the regression plot measures the correlation between network outputs and network targets.
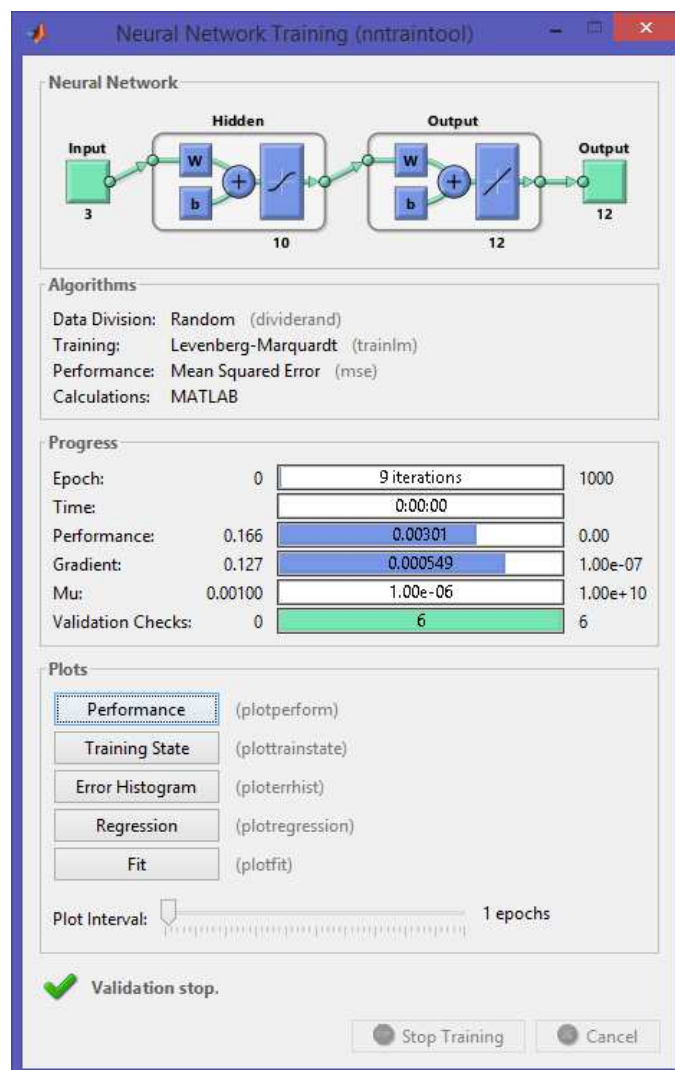
Figure 52: Neural Network Training

Figure 53 illustrates the iteration at which the validation performance achieved a minimum, the training continued for three more iterations before the training stopped. The validation and test curves are very similar, that does not indicate any major problems with the training. In case of over fitting, the test curve had increased significantly before the validation curve raised.
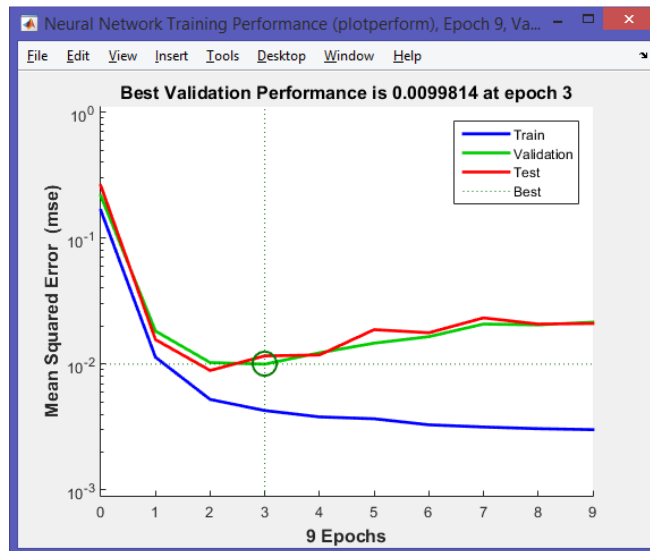
Figure 53: Neural Network Training Performance

Figure 54 highlights the previous thesis and complements the training performance with the curves for the gradient, the control parameter mu for the algorithm and the validation fail.
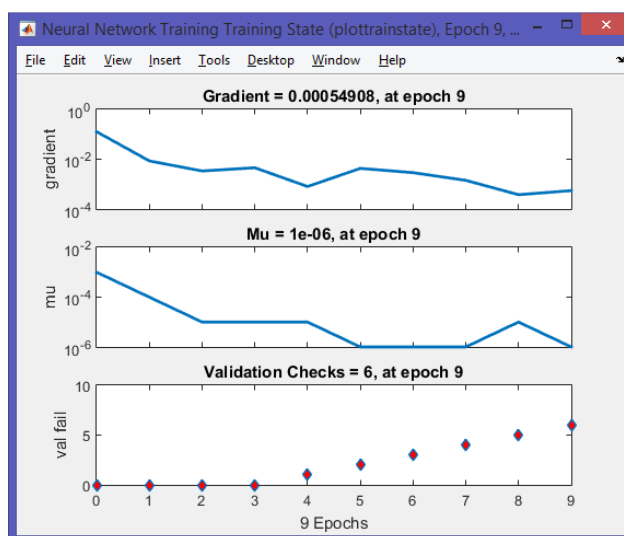
Figure 54: Neural Network Training State

Figure 55 shows the error histogram plot with the distribution of the network errors (see point five in chapter 3.5.1). This histogram provides a simple graphical view of accumulated errors including its dispersion and central tendency. The blue bars characterise training data, the green bars outline validation data and the red bars illustrate testing data. The error distribution takes on a Gaussian-like distribution shape over the exanimated range. The large centre peak indicates very small errors and leads to the assumption that output values are very to the target values. Most of the errors lie within the interval between -0.1016 and 0.1193. Outliers, which are data points where the fit is significantly worse than the majority of data, are located outside this interval. These outliers are also evident on the following testing regression plot in Figure 56. In case of a high quantity of outliers, it is necessary to investigate these input/target-vectors more in detail to avoid systematic failures in the network training. In this case, the ANN has provided a sufficiently accurate result.
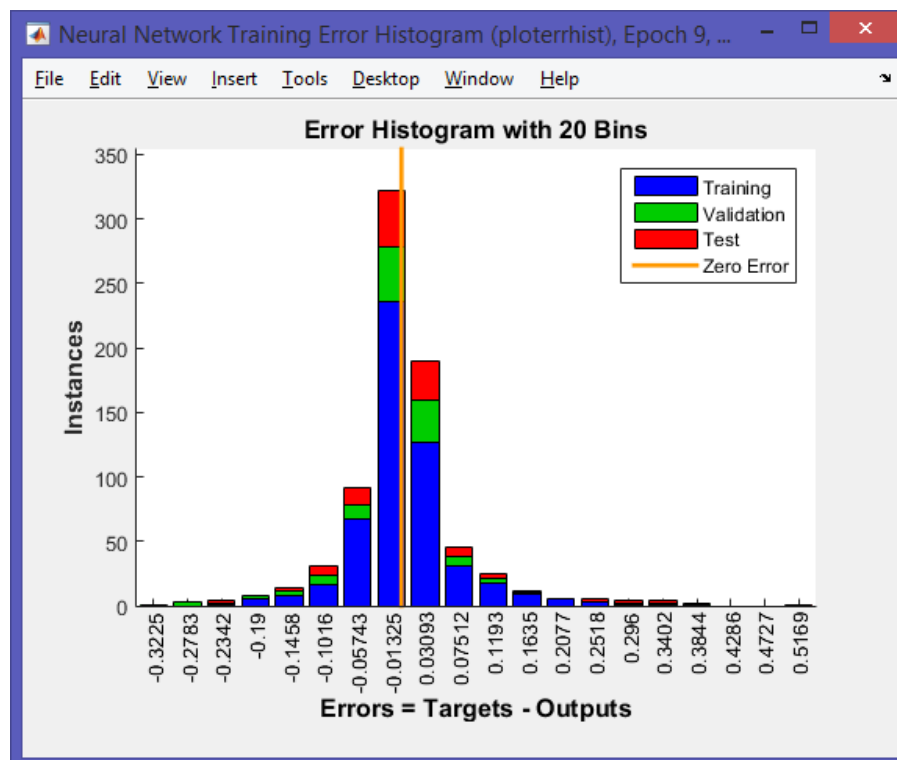
Figure 55: Neural Network Training Error Histogram

Figure 56 shows the regression plot which represents the correlation between the outputs and targets of the ANN. The dashed line in each plot (training, validation, test and all) reproduces the perfect result whereby the outputs are equal to the targets (see Table 19 and Table 20 in appendix 8.2.6). The solid line describes the best fit linear regression line between outputs and targets. As indicator for a good relationship between outputs and targets conducts a R-value close to one. If R is close to zero, then there is no linear relationship between outputs and targets. The ANN-training with the position offset data set is acceptable; the R-values in all four plots are above 99%, which represents sufficiently accurate results.
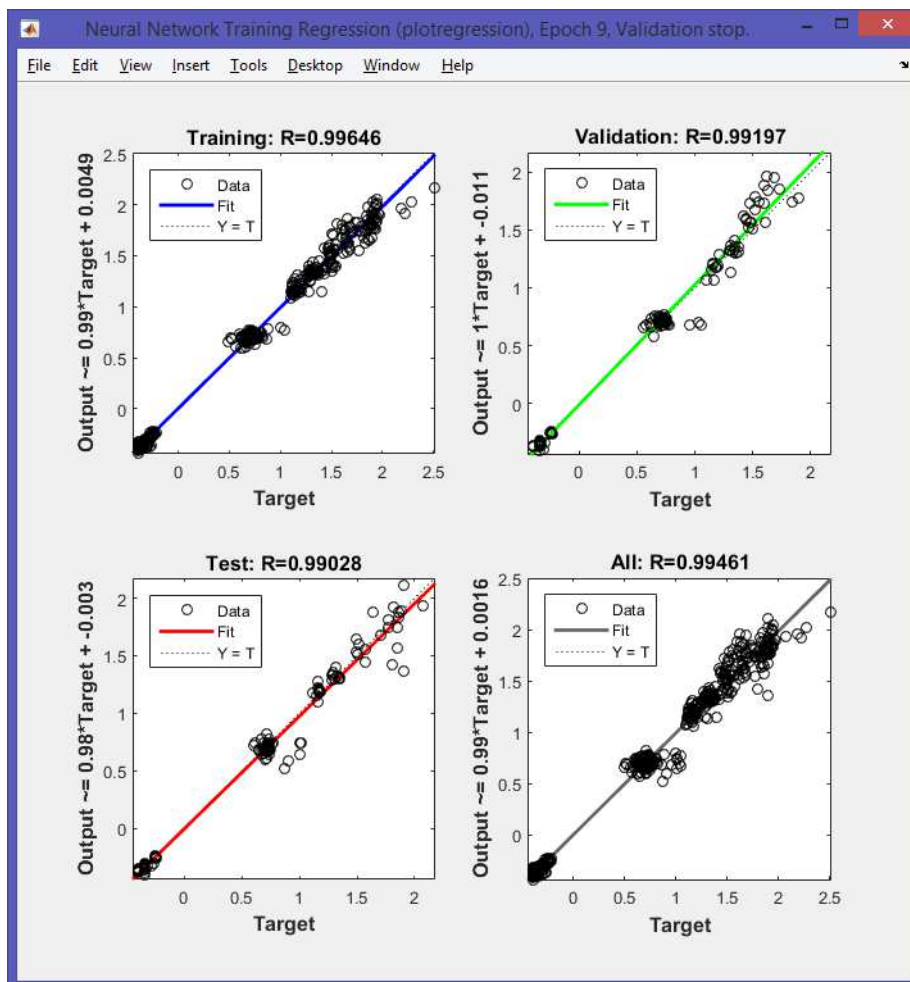
Figure 56: Neural Network Training Regression

5 Evaluation/Assessment of the Procedure

The aim of this chapter is the validation and verification of the theories in section three with the results and funds from section four. Descriptive statistics, such as standard deviations, means and percentages have been developed for the data that are relevant in the system waterfall scenario. After analysing the available data, possible modifications of the original parameters of the sensitivity analysis may become necessary to accommodate more significant information. The objective is that the outputs from the simulation coincide with the values from the measurement.

5.1 Selection of the DoE-Design

The DoE procedure starts with the determination of objectives for the experiment "spatial motion behaviour of parcels during singulation procedure" and selects afterwards the process factors for the study. The derived experimental design defines the laying out of the detailed experimental plan as previous step of doing a real experiment (parcel tower represents a 3D-arrangement). A well-chosen experimental design maximizes the amount of information that can be accessed from an acceptable volume of experimental effort. A completely full factorial design with interference columns proceeds results with high significance, but the high number of influencing factors and the resulting large variety of test runs create high effort. A fractional factorial design proceeds high number of influencing factors with less experiments, but it provides wrong results if interferences are underestimated. Preliminary tests have shown that the investigation of the spatial movement behaviour can be reduced substantially to three disturbance variables. Therefore, the waterfall singulation scenario was designed by the help of full factorial experimental design. Shear Modulus and coefficients of friction between parcel-parcel and parcel-ground were tested on four factor levels. The fixing of damping coefficient at an appropriately high level (0.9) has led to a significant reduction of required experiments and minimised the computing time to approximately seven minutes for one simulation run. The

real time singulation procedure (parcel tower tilts out of equilibrium, falls to the ground and parcels reach rest positions, see chapter 3.1) took 1.8 seconds (see program code PFC3D-parameter in appendix 8.2.2).

5.2   Results of Position Offset Analysis

The following diagrams show the absolute offsets (see point two in chapter 3.3.1) from the simulated single parcel centres' with regard to the examined real waterfall experiment. Every diagram represents the offset from each of the 64 runs depending on a change of another influencing factor. Diagram 2 exposes the offsets from the first parcel for all 64 simulation runs compared to the arithmetic mean from the conventionally measured attempts, if the influencing factor Shear Modulus has changed. The Shear Modulus varies between 1e09 and 5e10 N/mm² with two factor levels in between (5e9 and 1e10). Apart from a few outliers, the simulated parcel centres are positioned within a 0.2 m interval from the determined arithmetic mean of the measured attempts.
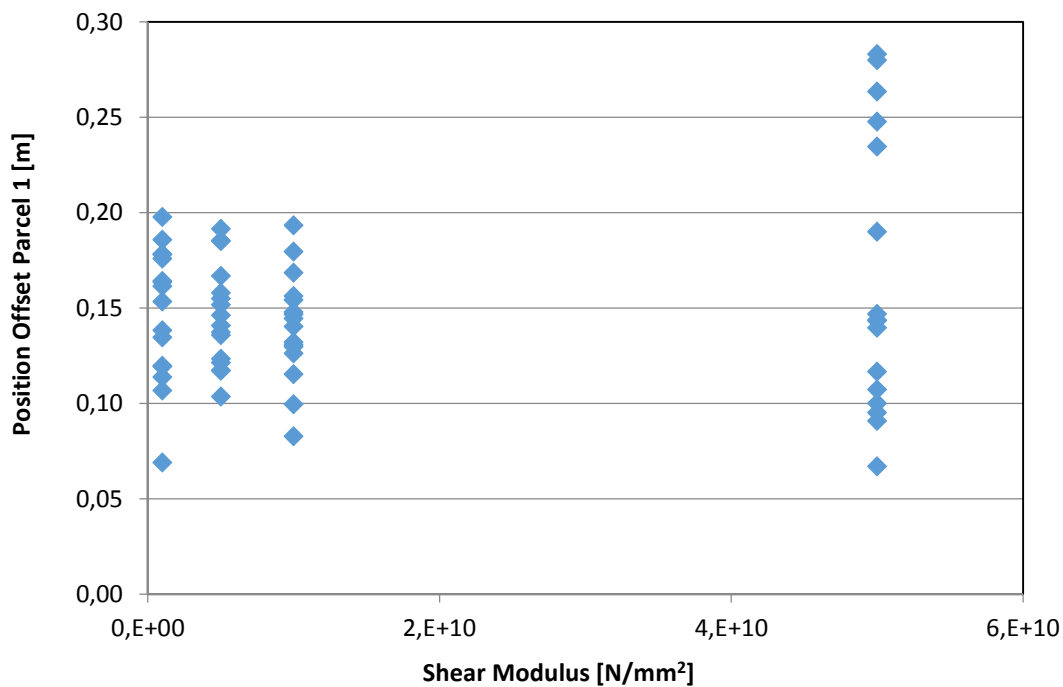
Diagram 2: Shear Modulus-Offset clump 1

Diagram 3 represents the position offsets from the second parcel centre due to the factor level variation of the influencing factor Shear Modulus. The factor levels were computed within the domain of 1e09 and 5e10 N/mm² whereby for all four examined factor levels the simulated parcel centres deviations are predominantly below the 15 centimetre mark. That means the Shear Modulus is a stable influencing factor, if it is settled within this area.
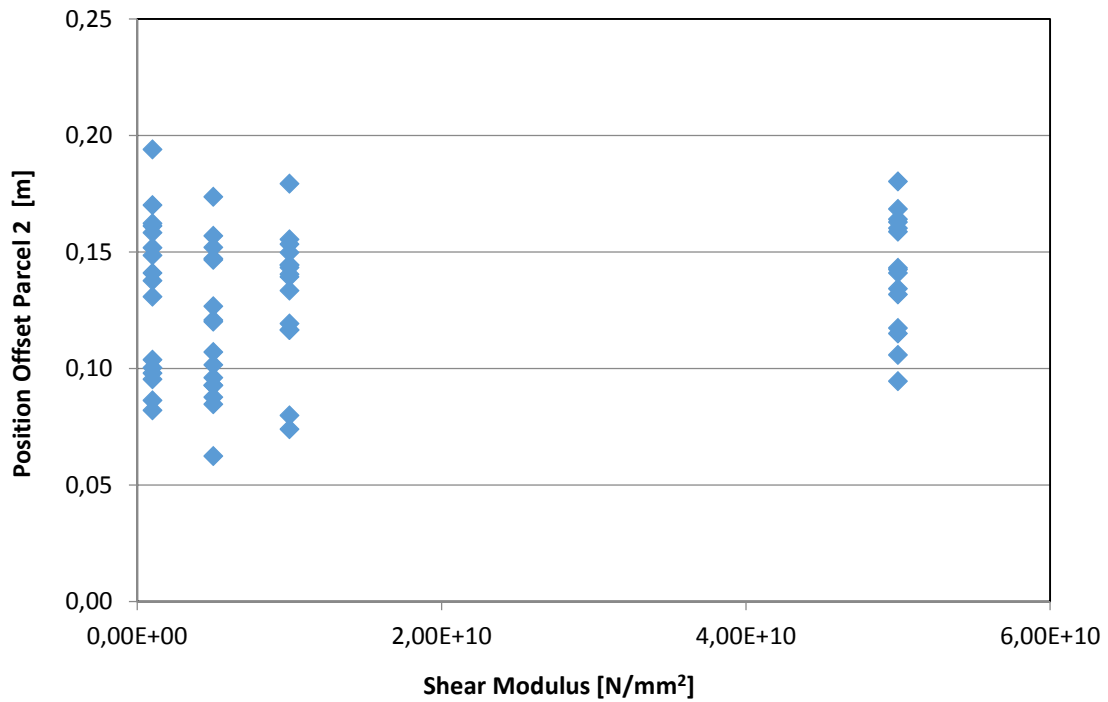
Diagram 3: Shear Modulus-Offset clump 2

Diagram 4 points out the simulated offsets from parcel centres from the third package due to determined average value from real experiment, if the friction coefficient between parcel-parcel has been varied on four different factor levels. The factor levels were settled on 0.2, 0.3, 0.4 and 0.5. The offsets of all 64 simulation runs are within an adequate range of 20 centimetres.
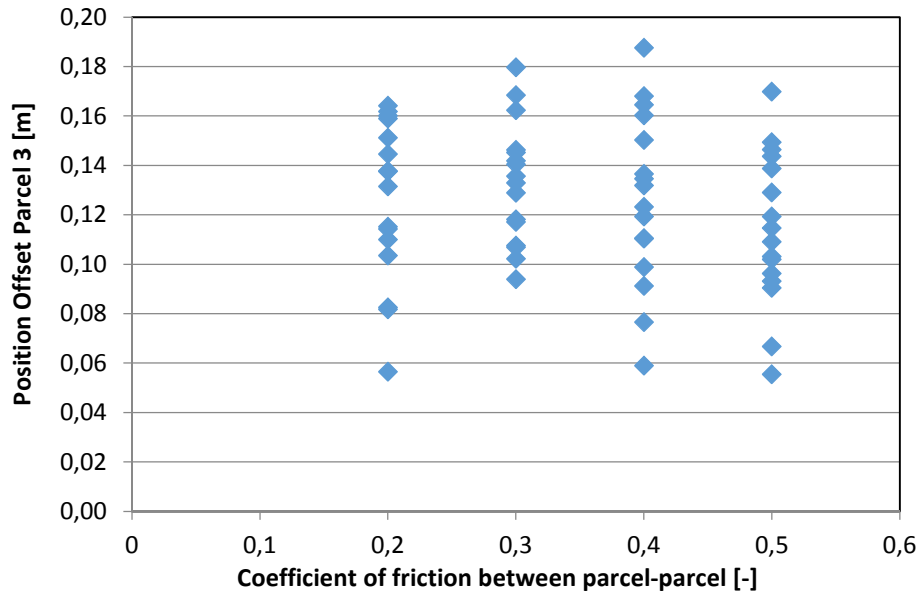
Diagram 4: Friction coefficient between pebble/pebble- Offset clump 3

Diagram 5 outlines the offsets from the fourth parcel (on the top of the parcel tower) with regard to the variation from coefficient of friction between parcel-ground. This kind of friction is in reality stronger than the friction between parcel-parcel. Therefore the factor levels are settled a bit higher on 0.4, 0.7, 1 and 1.3. For all of the 16 simulation runs on each of the four factor levels were computed adequate approximations compared to the calculated average mean of ten manually measured parcel drop tests (see Table 16 in appendix 8.2.4).
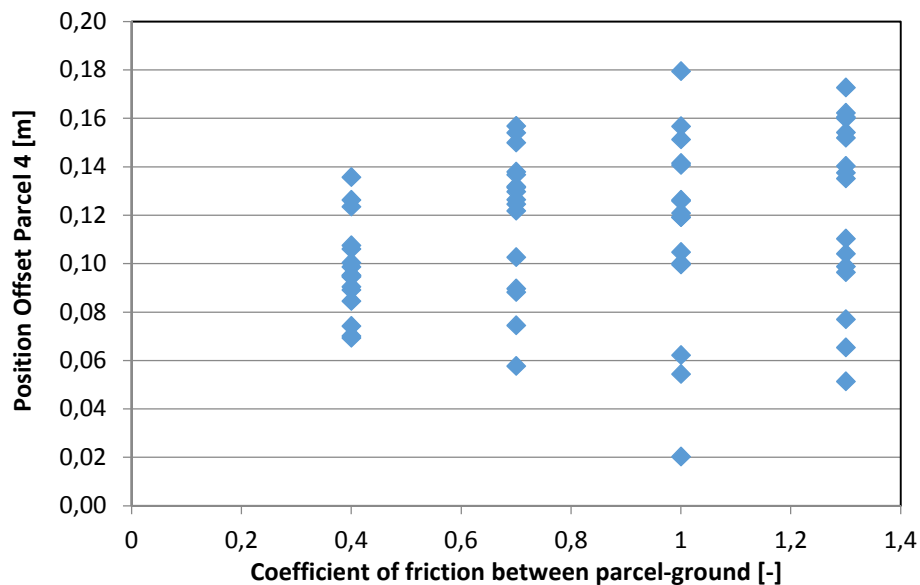
Diagram 5: Friction coefficient between pebble/facet- Offset clump 4

5.3   Evaluation and Interpretation of Offset Analysis

Table 11 classifies the Pearson correlation in order of the linear dependence between the different variables with respect to the reference values from Table 8. The evaluation table in subsection 4.1.2, which was derived from correlation plot, shows furthermore that the position offsets among themselves strongly influence each another. It is obvious that the offsets of the smaller parcels among themselves have high correlation coefficients, which can be explained due to very similar parcel constellation after the fall on the ground (see Figure 21). The following extract from correlation plot illustrates that there are strong linear dependencies between the offsets of parcel two, three and four, and minimal correlation between the first parcel and the other three packages (Figure 57).
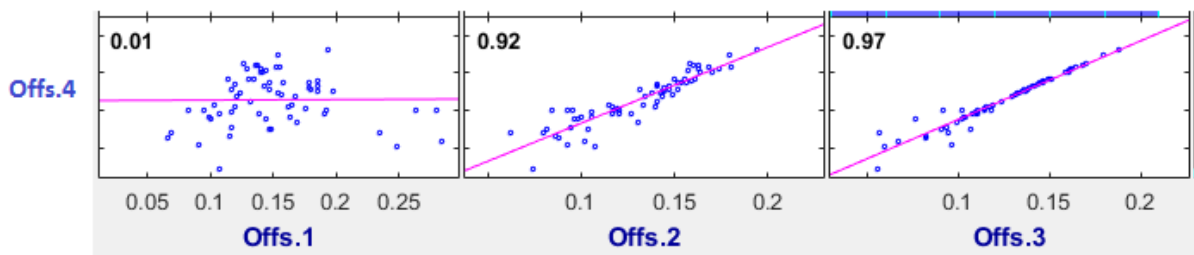
Figure 57: Correlation of position offsets among themselves

Clearly, it can be acknowledged that the Shear Modulus exerts a low positive linear correlation on the first parcel with its higher volume and weight (8 kg) than on the other three parcels (3.2 kg). There are low nonlinear correlation coefficients between Shear Modulus and the offsets from the smaller parcels (see Figure 58).
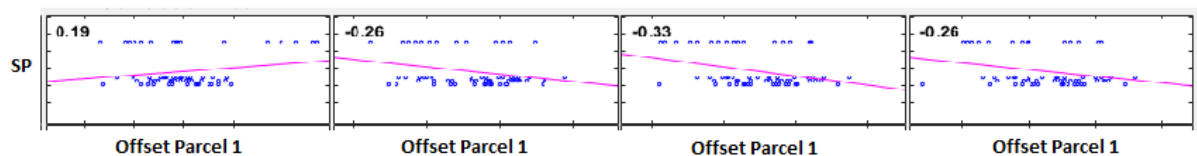
Figure 58: Correlation of Shear Modulus to position offsets

The coefficient of friction between parcel-ground and the Shear Modulus have generally stronger correlation coefficients on the quality characteristic "position offset" than the coefficient of friction between parcel-parcel. Low negative correlation coefficients indicate that there is a low nonlinear relationship between two considered variables (see Figure 59).
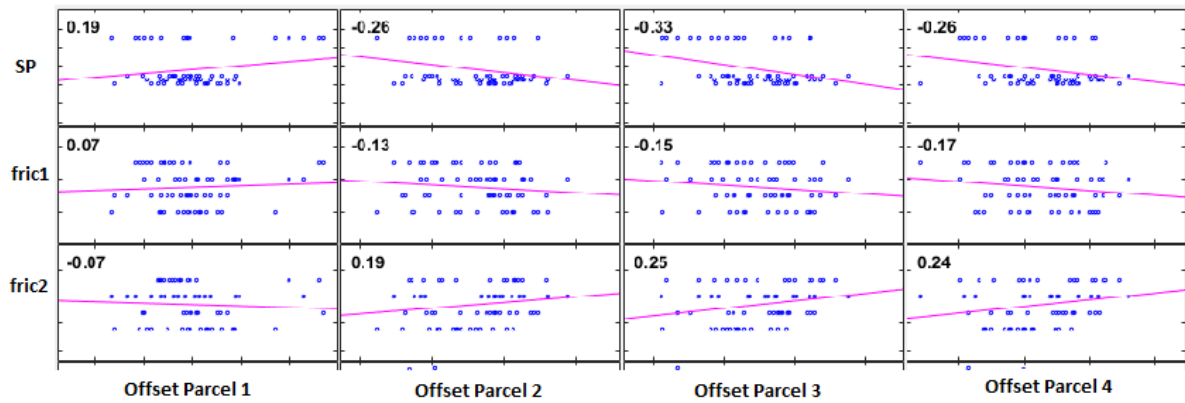
Figure 59: Comparison of all correlation coefficients from disturbance factors

Additionally, it was feasible to train an ANN (see Neural Fitting Tool in chapter 3.5) with the simulated position offsets. By comparison of a sufficient quantity of input/target pairs, it was possible to train the ANN until the network output has matched the target. The inputs of the ANN are characterised by the disturbance variables (see Table 18) and the targets are represented by the x-, y- and z-coordinates of parcels' centres (see Table 19). The computed outputs are listed in Table 20 in attached appendix 8.2.6.

This approach allows the forecasting of parcel offsets when the levels of disturbance variables are not at the same factor levels as they were simulated (see example in chapter 3.5.2).

5.4 Verification and Validation of Model

As mentioned in subchapter 3.3.3, the Pearson correlation coefficient is only applicable for normally distributed data. The influencing factors were set on four specific levels within simulation compatible ranges of values. Therefore, it is crucial to check whether the parcel offsets of all 64 simulation runs are normally distributed. Table 12 exhibits the normal distribution plots from the offsets of all four parcels. The plots document that the offsets (simulated parcel centres compared to the measured ones, see second point of chapter 3.3.1) of all parcels are normally distributed. The syntax *"H = chi2gof(X)"* accomplishes in Matlab "a chi-square goodness-of-fit test of the data in the vector X against the normal distribution with mean and variance estimated from X" [TMW15]. The vector X characterises the absolute parcel offsets (see Table 17 in appendix 8.2.5).

Table 12: Normal distribution plots from position offset analysis
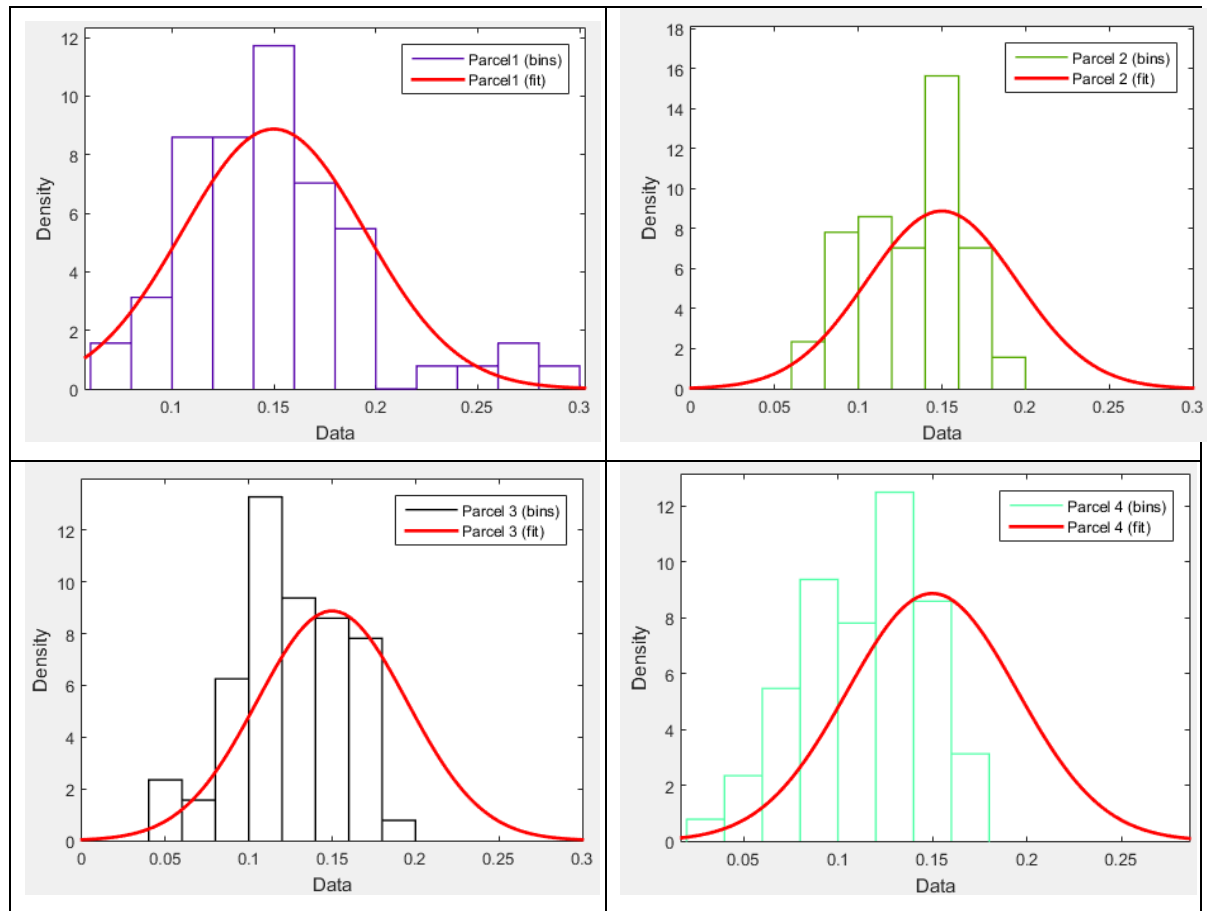
The null hypothesis states that "*X is a random sample from a normal distribution*" [TMW15]. If the result is *H = 0*, the null hypothesis "*cannot be rejected at the 5% significance level*" [TMW15]. The other way round (*H =1*), the null hypothesis can be rejected.

Entering the chi square distribution table with a significance level of 0.05 (alpha) and four degrees of freedom (df = 4, four parcel "vectors" composed of 64 offsets), it can be assumed that the chi square value (X^2) is equal to 9.488 [CSS15]. Matlab has computed a chi square statistic (chi2stat) of 2.5511.

Table 13 shows that the null hypothesis cannot be rejected because the condition is fulfilled. The offsets of all four parcels are normal distributed; the Pearson Correlation coefficient can be used as validation tool.

Table 13: Verification of normal distribution

Chi square statistic:	Chi square value:	Condition:	Result:
chi2stat = 2.5511	X^2 = 9.488	chi2stat < X^2	H = 0

5.5 Optimization of Target Parameters

The quality characteristic "position offset" as effect variable for the sensitivity analysis still offers possibilities for improvement. The implementation of a reliable gap counter (see chapter 6.3) to ensure a stable parcel flow requires the extension of the system boundaries (see chapter 3.3.1). This requires the additional considerations of other influencing factors and functional enhancement of the implemented simulation model in PFC3D. For this objective it is not enough to examine one single parcel tower, rather the emptying of a container with a high volume of parcels on a conveyor belt must be implemented and investigated.

Table 14 defines an assessment of a possible future quality feature that describes the singulation from 3D to 1D due to the significance of different criterions according specific arrangements of parcels (see Singulation Degree SD in chapter 6.3). A significance of one indicates that this criterion has prior priority because this parcel arrangement is complex to transform into a single-filed parcel flow. The criteria of lower significance will be achieved if the previous criteria have been met.

Table 14: Assessment of parcel arrangements

Significance	Parcel arrangement criteria
1	3D-parcel towers are worse than 2D-arrangements
2	The more parcels lie on top of each other, the worse is the singulation degree
3	Parcel overlapping in y-direction is worse than parcel jamming in x-direction
4	The more parcel overlapping in y-direction, the worse is the singulation degree
5	Assessment of parcel contact is inferior to contact freedom
6	The more parcels in the x-direction are in contact, the worse is the singulation degree

6 Summary and Outlook

Subchapters 6.1, 6.2 and 6.3 give a brief summary of the achieved goals of this master thesis and possible further research in the area of mechanical based singulation approaches in the parcel industry.

6.1 Résumé

The main reason for the use of DoE was to describe the spatial motion behaviour of parcels during singulation from 3D to 2D with certain accuracy. This procedure requires the optimisation of parameters and the identification of a characteristic target value. The DoE analysis filters the main influencing factors of 3D-parcel arrangements and helps in finding of an appropriate data set for singulation a pile of parcels into a two-dimensional grid. DEM-based simulation has not been studied in this context completely due to the fact that planar conveying processes represent the "status quo" in distribution centres. In the practical part of this mater thesis was performed a validation study from a spatial singulation arrangement. For realization of this intention and modelling a proper test scenario, the implementation of an experimental setup (parcel tower) in an appropriate simulation model (PFC3D) was necessary. This approach allows experimental testing of parcel accumulations without great expenses for test stands. For this purpose, an ANN was trained with the objective of forecasting parcel offsets when the levels of disturbance variables are not set at the same factor levels as they were simulated. The ANN identifies relationships between input and output variables by weighing of several inputs.

Additional to the obtained results, it was also checked if this singulation method is applicable to a large number of parcels (e.g. automated unloading of a container). Therefore, a future DoE-design for an ubiquitously applicable quality characteristic was prepared. Assessments from singulation procedures (3D to 1D) should be processed by the help of an uniform SD (see chapter 6.3).

6.2 Outlook

The status quo for discharging large numbers of parcels from a container is processed manually or by the help of gripper systems with a limited throughput of 1,000 parcels per hour (see state of the art in chapter 2.3). The increasing transport- and handling-volume of this industry requires innovative solutions for increasing the current singulation rate of conventional parcel centres from 20,000 to 50,000 parcels per hour ([BIE15]; [CRR+14]). Through the combination of several mechanically based singulation principles like different velocity fields (2D) or vertical gaps (3D), it shall be possible to implement various material handling systems that are able to singulate a pile of parcels into a single-filed parcel flow with defined gaps in between (3D to 1D). The installed technology has to be as economical as possible; the period of amortization must be paid off through long product life cycles and low operating costs. Furthermore, the new mechanical based singulation approaches have to convince through flexibility and multi-functionality. Very expensive robot systems can be gradually replaced and overworked employees can be relieved. Therefore it requires to disburden people and to optimize used production resources, especially the development of elastic conveyors for parcel impact absorption offers a big potential for improving 3D to 2D-based, mechanical parcel singulation. Further may be filed on the surface texture of the parcels in order to minimize friction and thereby facilitating the separation procedure.

6.3 Possible Further Research Activities

Another possible further research activity could be the exploration of an alternative energy consumption system for parcels that fall from a vertical gap of two subsequent belt conveyors. If the parcels would be absorbed so resiliently as possible by conveyors, vertical gaps could be increased without damage of parcels and higher singulation degrees could be achieved. Possible damage of packages contents must be avoided; therefore fall heights for the waterfall scenario are limited. This limitation restricts also the possible singulation quality whereby further studies regarding inhomogeneity of bulk structures like dimensions, weight, contour, surface condition, deformation, wedging effect, etc. are required.

This master thesis expresses the quality of spatial motion behaviour of a parcel tower by the help of DEM-based simulation. Future examinations can take this consideration as basis for developments of more accurate singulation models. Advanced singulator models may include a complete counter system, which reliably counts the gaps between the parcels and assures sustainable singulation of large numbers of parcels without excessive labour input. Different parcel arrangements have to be considered for this vision; the next two figures provide a brief view of this approach. It is based on zoning of the control room in constant length intervals which is installed normal to the conveying direction and determines the singulation degree by counting overlapping packages.

However, the determination of the SD could also take place in an alternative way. The side surface of a parcel cannot be considered as totally straight-lined; therefore, the determination of the singulation degree could also be effected via the curvatures of the parcels. By partition of parcels surface into convex or concave curvature, the counting of contact points could be realized and may help to define the SD. This consideration requires the determination of the parcel number from which a parcel tower is composed of. This classification number "i" outlines for the 3D-scanning (see Figure 60) that there rests two parcels lie on top of each other (i=2) in the first control room. For the second control room, i is equal to three, which means that three parcels lie on one another. The singulation of such parcel bulks represents the target area for the waterfall approach.

By tilting the parcel tower over the edge of an upper conveyor belt, the 3D-parcel tower will be singulated to a 2D-arrangement. If the single parcels begin to slip on each other, the coefficient of friction between the parcels can no longer hold the pile of parcels together.
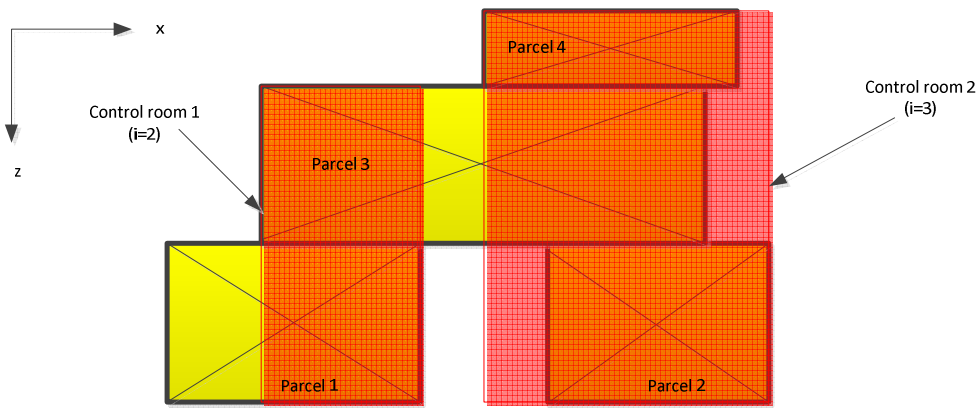
Figure 60: 3D-scanning

Figure 61 demonstrates the same methodology for the 2D-scanning in the plane. If the parcels are not aligned on one straight line, the number of overlapping parcels can be identified by the help of control rooms. This type of parcel arrangement is predestined for the singulation via deflection that is mentioned in the first point of chapter 2.3.3.
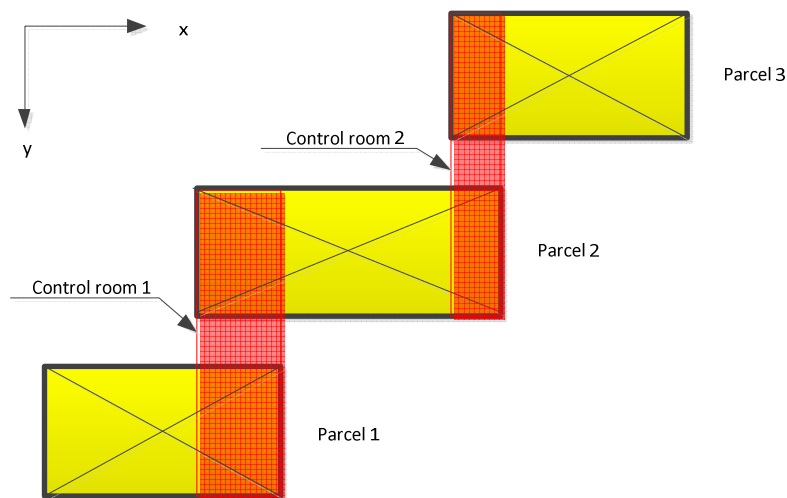
Figure 61: 2D-scanning

Figure 62 provides a theoretical mathematical formulation by determination of the singulation degree through count rating of parcel gaps within a control room. The examination starts with 3D-Scanning by counting the dimension of parcel towers, than follows the 2D-checking and last but not least the 1D-assessment due to parcel overlapping. The control variable i defines the level of overlapping, e.g. i equal to five identifies a parcel tower for 3D-scanning where five parcels lie on top of each other. This variable i takes for 2D- and 3D scanning the same task and provides by multiplication with the number of involved parcels an informative classification number for parcel disorder. If the total quantity of parcels n_{total} is divided by the sum of this characteristic number, the single singulation degrees for each scanning (SD_z, SD_y and SD_x) can be determined. The final singulation degree SD is calculated by the sum of all three partial singulation degrees whereby each individual term counts one third.

Start

3D Scanning
Checking of the parcel heap due to overlappings in z-direction:

$$SD_Z = \frac{n_{total}}{\sum_{i=1}^{\infty}\left(i^2 * n_{Zi}\right)}$$

2D Scanning
Checking of the parcel heap due to overlappings in y-direction:

$$SD_Y = \frac{n_{total}}{\sum_{i=1}^{\infty}\left(i^2 * n_{Yi}\right)}$$

1D Scanning
Checking of the parcel heap due to overlappings in x-direction:

$$SD_X = \frac{n_{total}}{\sum_{i=1}^{\infty}\left(i^2 * n_{Xi}\right)}$$

Assembling of Singulation Degree (SD):

$$SD = \tfrac{1}{3} * \left(SD_Z + SD_Y + SD_x\right)$$

End
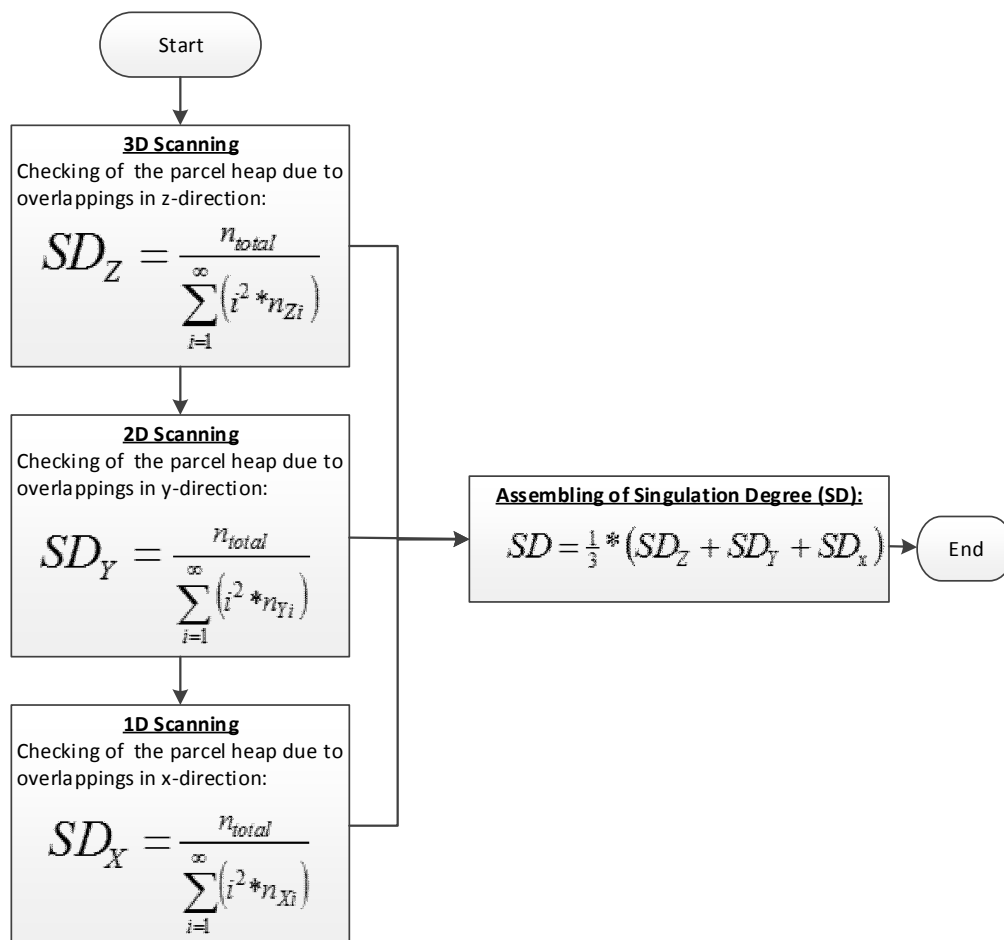
Figure 62: Determination of the Singulation Degree

7 Lists

This master thesis specifies in the following five subchapters the lists of references, figures, diagrams, tables and abbreviations. Figures visualize and depict a subject that is described in the theory, represent the implementation steps of used software tools (PFC3D from Itasca and Neural Toolbox from Matlab) or explain specific parts of the program code. Diagrams illustrate the achieved results of the position offset analysis. Tables' exhibit overviews in the theoretical part of this thesis and list achieved results in the practical part. The last list documents the used abbreviations.

7.1 List of References

[AF09]   Arnold, Dieter; Furmans, Kai: *Materialfluss in Logistiksystemen.* Berlin/Heidelberg: Springer 2006, 2009. - e-ISBN 978-3-642-01405-5

[AIK04]   Arnold, Dieter (Ed.); Isermann, Heinz (Ed.); Kuhn, Axel (Ed.) et al.: *Handbuch der Logistik.* 2. Aufl., Berlin : Springer, 2004.

[BHA14]   Bharadwaj, Rahul: *What is Discrete Element Method?* URL http://www.powderbulksolids.com/article/what-discrete-element-method-09-10-2014 - Call date: 16.03.2015

[BEU14]   Beumergroup (Ed.): *Automatic Parcel Singulator*, 2014, Firmenschrift.

[BIE15]   Bundesverband Internationaler Express- und Kurierdienste o.V. (BIEK) (Ed.): *KEP-Studie 2013.* URL file:///D:/Eigene%20Dateien/Downloads/BIEK_KEP-Studie_2015.pdf – Call date: 02.10.2015

[BLO08]   Blomeyer, Niels Arwed: *Erweiterung und Verifikation von Auslegungsverfahren für Hochleistungs-Schneckenförderer für Schüttgut.* Dissertation, Universität München, Fakultät Maschinenwesen, 2008.

[CRR+14]   Cao, Liu; Richter, Klaus; Richter, Christian et al.: *Simulation der peristaltischen Förderung von Stückgütern als Schüttgut*. Paper, Universität Magdeburg, Institut für Fabrikbetrieb und – Automatisierung, 2014.

[CS79]   Cundall, Peter; Strack, O.D.L.: *A Discrete Numerical Model for Granular Assemblies*. Géotechnique, 29, pp. 47 - 65 (1979).

[CSS15]   The Chi Square Statistic - probability level (alpha). URL http://math.hws.edu/javamath/ryan/ChiSquare.html - Call date: 18.10.2015

[CUN88]   Cundall, P.A.: *Computer Simulations of Dense Sphere Assemblies*, Micromechanics of Granular Materials, Satake, M., Jenkins J.T. (ed.), pp. 113-123, 1988.

[DB04]   Demuth, Howard; Beale, Mark: *Neural Network Toolbox – For Use with MATLAB – User's Guide (Version 4)*. URL http://www.csse.monash.edu.au/courseware/cse5301/2006/nnet.pdf - Call date: 16.07.2015

[DHL15]   DHL (Ed.): *Damit ihre Ware immer gut ankommt!* URL https://www.dhl.de/content/dam/dhlde/downloads/pdf/geschaeftsku nden/dhl_geschaeftskunden_verpackungsbroschuere_09_2015.pdf - Call date: 04.10.2015

[DvW04]   Delfos, Tom; van Wijngaarden, Erik: *Singulator - Vereinzelungsförderanlage.* European Patent Specification, EP20030075403, 2004.

[FHS12]   Fikse, K.; Haneyah, S.W.A.; Schutten, J.M.J.: *Improving the performance of sorter systems by scheduling inbound containers*. Working paper, University of Twente, 2012.

[FWJ13]   Fritz, Matthias; Wolfschluckner, Andreas; Jodin, Dirk: *Simulation von Paketen im Pulk*. Paper, Universität Graz, Fakultät Maschinenbau, 2013.

[FWL+15]   Fritz, Matthias; Wolfschluckner, Andreas; Landschützer, Christian et al.: *Simulation of parcel singulation processes – a DEM approach*. Conference/Paper: Proceedings of the XXI International Conference MHCL'15, venue: FME Belgrade, 2015.

[GUD05]   Gudehus, Timm: Logistik - *Grundlagen, Strategien, Anwendungen*. Berlin/Heidelberg/ New York: Springer, 2005. - ISBN 3-540-24113-2.

[HÄF98]   Häfner, Günther: *Simulation im Entwicklungsprozess*. In: *Wissensmanagement - Schritte zum intelligenten Unternehmen*, Bürgel (Ed. Bd.): Springer Berlin Heidelberg, 1998, pp 175-188

[HEK05]   Hartung, Joachim; Elpelt, Bärbel; Klösener, Karl-Heinz: Statistik - *Lehr und Handbuch der angewandten Statistik*. München: Oldenbourg Wissenschaftsverlag 2005. – e-ISBN 3-486-57890-1

[HHD15]   Hudson Beale, Mark; Hagan, Martin T.; Demuth, Howard B.: *Neural Network Toolbox – User's Guide (R2015a)*. URL http://www.mathworks.com/help/pdf_doc/nnet/nnet_gs.pdf - Call date: 16.07.2015

[ICG15]   Itasca Consulting Group, Inc. (2015) PFC - *Particle Flow Code in 2 and 3 Dimensions*, Version 5.0, Documentation Set of version 5.00.20. Minneapolis: Itasca.

[INT15]   Intralogistics (Ed.): *Linear Parcel Singulator*. URL http://intralogistics.fivesgroup.com/solutions-products/products/singulators/linear-parcel-singulator.html - Call date: 04.05.2015

[ITL14]   Institut für Technische Logistik (Ed.): *Tätigkeitsbericht 2014*. URL http://portal.tugraz.at/portal/page/portal/Files/i3090/files/T%C3%A4tigkeitsbericht%202014_online_Version.pdf – Call date: 04.10.2015

[JK12]   Jakob, Christian; Konietzky, Heinz: *Particle Methods - An Overview*. Handbook, Universität Freiberg, Chair for Rock Mechanics, 2012.

[JtH12]   Jodin, Dirk; ten Hompel, Michael: Sortier- und Verteilsysteme - *Grundlagen, Aufbau, Berechnung und Realisierung*, Berlin/Heidelberg: Springer, 2006, 2012. – e-ISBN 978-3-642-31290-8.

[KA05]   Karaca, Hüseyin N.; Akınlar, Cüneyt: *A Multi-camera Vision System for Real-Time Tracking of Parcels Moving on a Conveyor Belt*.

In: Yolum, Pınar; Güngör, Tunga; Gürgen, Fikret; Özturan, Can (Ed. Bd.): *Computer and Information Sciences – ISCIS 2005*, Istanbul, Springer Verlag, 2005, pp 708-717.

[KAN15]   Kannan, Nari: *Decision - Making with Cause - and Effect Analysis and DOE*. URL http://www.isixsigma.com/tools-templates/cause-effect/decision-making-cause-and-effect-analysis-and-doe/ - Call date: 12.08.2015

[KEL13]   Keller, Daniela: *Analyse von Zusammenhängen: Korrelation*. URL http://www.statistik-und-beratung.de/2013/05/analyse-von-zusammenhangen-korrelation/ - Call date: 13.07.2015

[KLE13]   Kleppmann, Wilhelm: Versuchsplanung - *Produkte und Prozesse optimieren*. München/Wien: Carl Hanser 2013. - e-ISBN 978-3-446-43791-3

[KRÄ03]   Krämer, Walter: Statistik verstehen – *Eine Gebrauchsanweisung*. München. Piper 2003. - ISBN-13: 9783492230391.

[mCi15]   maltCertinstitut (Ed.): *ASM Vision : Technische Eigenschaften* URL   http://www.malt-cert.de/malz/files/maltcert_select_mit_asm_vision_informationen_stand_feb2013.pdf - Call date: 07.09.2015

[MD53]   Mindlin, R. D.; Deresiewicz H.: *Elastic spheres in contact under varying oblique forces*. J. Appl. Mech., 20, 327-344 (1953).

[MÖH83]   Möhle, Bernd: *Zum Bewegungsverhalten von Stückgütern beim Abweisen auf Gurtförderern beim Ausrichten und Abweisen*. Dissertation, Universität Braunschweig, Fakultät Maschinenbau und Elektronik, 1983

[PBF+06]   Pahl, Gerhard; Beitz, Wolfgang; Feldhusen, Jörg et al.: Konstruktionslehre - *Grundlagen erfolgreicher Produktentwicklung, Methoden und Anwendung*. Berlin/Heidelberg: Springer 2003, 2005, 2007. - ISBN-13 978-3-540-34060-7

[POH08]   Pohl, Almut: *Diese Wände sind nicht von Pappe*. URL http://www.catse.ethz.ch/news/Holzforschung_Schweiz_01-08_Artikel.pdf - Call date: 30.09.2015

[POS15]   Post   (Ed.):   *Verpackungsmaterial*.   URL

https://www.post.at/privat_versenden_paket_verpackungsmaterial
.php - Call date: 04.09.2015

[SIE09]   Siemens (Ed.): *An intelligent combination: the new Siemens con-veyor and sortation systems*. SILOG News - Automation for post, courier, express and parcel services, 2009. - Firmenschrift.

[SIE13]   Siemens (Ed.): *Solutions for seamless parcel logistics – fast and reliable   (2013)*.   URL http://w1.siemens.ch/mobility/global/SiteCollectionDocuments/en/l ogistics/postal-automation/solutions-for-seamless-parcel-logistics-en.pdf - Call date: 04.10.2015

[SBH10]   Siebertz, Karl; van Bebber, David; Hochkirchen, Thomas: Statisti-sche Versuchsplanung - *Design of Experiments (DoE)*. Ber-lin/Heidelberg: Springer 2010. - e-ISBN 978-3-642-05493-8

[TKK15]   ThyssenKrupp   Krause   (Ed.):   *ParcelRobot*.   URL http://www.robotiklogistik.de/fileadmin/user_upload/services/press e/broschueren/Brochure_ParcelRobot_TKKrause.pdf- Call date: 05.10.2015

[TMW15]   The MathWorks: Statistics Toolbox - For Use with MATLAB. URL http://www.pi.ingv.it/~longo/CorsoMatlab/OriginalManuals/stats.p df - Call date: 18.10.2015

[VAN15]   Vanderlande   Industries   (Ed.):   *Parcel   and   Postal*.   URL https://www.vanderlande.com/ - Call date: 13.05.2015

[WB96]   Whelan, Paul F.; Batchelor, Bruce G.: *Automated Packing Sys-tems - A Systems Engineering Approach*. In: IEEE Transactions on systems, man and cybernetics - Part A: Systems and Humans, VOL. 26, NO. 5, September 1996.

[WIE11]   Wieczorek, Dorothee: *Empirische Entwicklung von Prognosemo-dellen für die Auslegung von Rollenfördermodulen.* Dissertation, Universität Dortmund, Fakultät Maschinenbau, 2011.

[YYJ+14]   Yu1, Wooyeon; Yang, Jaekyung; Jung, Hoon et al.: *Design and Implementation of Robotic Parcel-Sortation systems*. URL file:///D:/Eigene%20Dateien/Downloads/smartcr_vol4no2p2.pdf   - Call date: 06.02.2015

7.2   List of Figures

7.3   List of Diagrams

7.4   List of Tables

7.5 List of Abbreviations

α_k	learning rate of ANN
ANN	Artificial Neural Network
B	Branch
BOOL	Boolean value
C	Conveying
CE	Computer Experiment
CEP	Courier, Express and Parcel services
cmat	contact model assignment table
HUB	Hauptumschlagsbasis
DEM	Discrete Element Method
DoE	Design of Experiments
DP	Damping coefficient
DP_n	Discharging Points of n discharging points
Dr	Drain, sink
E	Effect of an influencing factor on the quality characteristic
$E_k^{(i)}$	Edges of a facet
G or (SP)	Shear Modulus
g_k	Current gradient of ANN learning algorithm
I	Identification
i	Dimension of parcel tower
INT	Integer number
$F^{(i)}$	Number of facets
FLT	Floating-point number
fric1	Friction coefficient between parcel-parcel
fric2	Friction coefficient between parcel-ground
M	Merge
MBS	Multi Body Simulation
mse	mean square error
n	number of parcels
N_i	Number of network inputs in ANN
N_l	Number of network layers in ANN

ODE	Ordinary Differential Equation
p	Input matrix of ANN
PFC3D	Particle Flow Code in 3 Dimensions
R^i	Radii od pebbles
R	Regression value
RFID	Radio Frequency Identification
SD	Singulation Degree
So_m	Source of m charging points
SP	Shear Modulus
t	Target matrix of ANN
μ	Coefficient of friction
v	Translation in PFC3D
$v^{(k)}$	Vertexes of walls in PFC3D
VEC	3D vector of floating-point numbers
w	Rotation in PFC3D
W	Waiting
x^i	Positions of pebbles
x_k	vector of current weights and biases
y	Analysed output variable in regression analysis

8 Appendix

Subchapter 8.1 includes the published short text for the TUG-online system in German and in English. Subchapter 8.2 lists the different parts of the program code in PFC3D (8.2.1 to 8.2.3) and the tables for the DoE, the results of the real measurements (8.2.4) and the input- and output-tables of the ANN (8.2.6).

8.1 Appendix 1 – Published Short Text

1. Publizierte Kurzfassung im TUG-System:

   Die vorliegende Arbeit befasst sich mit der experimentellen Untersuchung, sowie der numerischen Simulation von Paketen im Pulk auf Basis der Diskreten Elemente Methode (DEM) während der Vereinzelung. Die Vereinzelung großer Paketzahlen mittels Roboter durch Greifen und Transportieren einzelner Pakete erfordert Leerfahrten, weshalb dieser Ansatz den immer steigenden Paketdurchsätzen im Umschlag innerhalb von Distributionszentren nicht nachkommt. Die Vereinfachung des Vereinzelungsmechanismus auf schlichte mechanische Wirkprinzipien wie das Abweisen von Stückgütern in der Ebene (zweidimensional) oder das Fallenlassen von großen Paketzahlen aus einer bestimmten Höhe mittels Wasserfallprinzips (dreidimensional) stellt großes Entwicklungspotential hinsichtlich der Machbarkeit des mechanischen Handlings von 3D-Paketanhäufungen dar.

   Das Hauptaugenmerk dieser Arbeit liegt in der Implementierung und experimentellen Untersuchung eines Wasserfallszenarios, bei welchem ein Paketturm aus einer Höhe auf ein darunterliegendes Förderband fallen gelassen wird. Für die Umsetzung dieses Models hat sich das DEM-basierende Anwenderprogramm PFC3D (Particle Flow Code Three Dimensional) als am geeignetsten herausgefiltert. Da die Erzeugung eines Körpers mithilfe der DEM nur durch das Zusammensetzen einer Vielzahl von Partikeln gelingt, musste die Annahme erfolgen, Stückgut gewisser-

maßen als Schüttgut zu behandeln. Dieser Ansatz erfordert eine entsprechende Validierung und Verifizierung des simulierten, räumlichen Bewegungsverhaltens von Paketen während der Vereinzelung von 3D auf 2D um die Richtigkeit dieses jungen Zweiges in der Logistik zu untermauern. Mithilfe der statistischen Versuchsplanung (DoE) wurde das System „Wasserfall" auf seine wichtigsten Parameter untersucht und mit einem messbaren Qualitätsmerkmal „Positionsabweichungen" beschrieben. Dazu wurden wichtige Einflussfaktoren auf unterschiedliche Stufen gestellt und dann miteinander variiert. Durch Kombination der einzelnen Faktorstufen und den Abgleich der Simulationsergebnisse mit einer realen, experimentellen Versuchsreihe, konnten die Wertebereiche für die Einflussfaktoren so eingegrenzt werden, sodass eine gute Korrelation zwischen simulieren und experimentell bestimmten Paketpositionen (x, y, z) zustande kam.

2. Published short text in English:

This master thesis deals with the singulation of a parcel pile (3D) to a two-dimensional grid (2D). If parcels are jammed and dammed, the material flow is interrupted and this circumstance causes bottlenecks in the realization of a proper throughput in material handling systems. The separation from a pile of parcels by gripping and transporting individual parcels has so far emerged as not optimal, because these approaches are only feasible with great work input and associated high costs. The current state of the art leads to an enormous potential for development due to cost effectiveness and work simplification. If high-tech automated singulation mechanisms are reduced to simple mechanical based separation principles like deflection in a plane (2D) or introduced vertical gaps like the waterfall scenario (3D), it should be possible to meet the increasing requirements of the CEP (Courier, Express and Parcel)-services' industry. Therefore, the Discrete Element Method (DEM) based simulation was applied to the spatial singulation process of large numbers of parcels with the aim to avoid unnecessary costs in the development phase.

The main focus of this work was the implementation of a waterfall scenario in an appropriate simulation tool, whereby a parcel pile falls from an upper positioned level to the ground. The DEM based user program PFC3D (Particle Flow Code Three Dimensional) has filtered out as the most suitable tool for transforming this test scenario into a simulation model, it builds on the generation of bodies by accumulations of huge quantities of particles with specific properties. Thereby, it was mandatory to make the assumption of handling general piece cargo as a kind of bulk good. For validating the quality of the simulation model, it was necessary to describe the waterfall scenario with a measurable quality criterion "position offset". By the help of Design of Experiments (DoE), the main influencing parameters (e.g. coefficients of friction or Shear Modulus) were fixed on four different factor levels and were varied with each other. Through the optimal combinations of each individual factor levels and the comparison of the simulation results with a real set of experiments, the best possible data ranges for the factors could be determined. The objective of high correlations between simulated and manually measured values was put into practise.

8.2   Appendix 2 – Additional Information

8.2.1   Program Code PFC3D-Base

```
title 'Base'

@Simparameter
[Poi = config(1,k1)]     ;Poisson's ratio Parcel

@SetDisturbanceVariables
[SP    = DisturbanceVariables(1,var1)]  ;Shear Modulus
[fric1 = DisturbanceVariables(2,var2)]  ;Friction Parcel-Parcel
[fric2 = DisturbanceVariables(3,var3)]  ;Friction Parcel-ConveyorBelt

domain condition destroy extent 0 [c1x+c2x] -0.05 1.25 @h 0.7

cmat default model hertz property hz_shear 1.0e10 hz_poiss 0.3 dp_mode 0 dp_nratio 0.1
dp_sratio 0.1 fric @fric2
cmat default type pebble-pebble property hz_shear @SP hz_poiss @Poi dp_mode 0 dp_nratio @DP
dp_sratio @DP fric @fric1
cmat default type pebble-facet property hz_shear 1.0e10 hz_poiss 0.3 dp_mode 0 dp_nratio 0.1
dp_sratio 0.1 fric @fric2

;Generation of LowerConveyorBeltLeft
wall generate id 1 name LowerConveyorBeltLeft polygon ...
          @c2x 0 @h ...
          @c2x 0.6 @h ...
          [c1x+c2x] 0 @h ...
          [c1x+c2x] 0.6 @h

;Generation of LowerConveyorBeltRight
wall generate id 2 name LowerConveyorBeltRight polygon ...
          @c2x 0.6 @h ...
          @c2x 1.2 @h ...
          [c1x+c2x] 0.6 @h ...
          [c1x+c2x] 1.2 @h

;Generation of UpperConveyorBelt
wall generate id 3 name UpperConveyorBelt polygon ...
          0 0 0 ...
          0 1.2 0 ...
          @c2x 0 0 ...
          @c2x 1.2 0

;Generation of WaterfallConstraint
wall generate id 4 name WaterfallConstraint polygon ...
          @c2x 0 @h ...
          @c2x 1.2 @h ...
          @c2x 0 0 ...
          @c2x 1.2 0

;Generation of Deflector1
[l1xa = xa1 + la1] ;end position of Deflector1
wall generate id 5 name Deflector1 box @xa1 @l1xa 0 0.01 [h + 0.08] [h + 0.10]
wall rotate axis 0 0 1 angle @alpha point @xa1 0 0 range id 5 10

;Generation of Deflector2
[l2xa = xa2 + la2] ;end position of Deflector2
wall generate id 11 name Deflector2 box @xa2 @l2xa 1.2 1.21 [h + 0.08] [h + 0.10]
wall rotate axis 0 0 1 angle @betha point @xa2 1.2 0 range id 11 16

;Generation of SideFences
wall generate name SideFence1 plane dip 90 ddir 0 position 0 0 0
wall generate name SideFence2 plane dip 90 ddir 0 position 0 1.2 0

wall group SideFences range id 4,15 ;17
cmat add model hertz property hz_shear 1.0e10 hz_poiss 0.3 dp_mode 0 dp_nratio 0.1 dp_sratio
0.1 fric 0.3 range group SideFences
cmat apply

;Generation of Parcels
geometry set Parcel_1
geometry generate group Parcel box 0 0.4 0 0.31 0.005 0.145
[vol1 = 0.4*0.31*0.14] ;Volume of Parcel_1
```

```
[mas1 = 8] ;Mass of Parcel_1
[den1 = mas1 / vol1] ;Density of Parcel_1
clump template create name Parcel_1 geometry Parcel_1 surfcalculate ...
    bubblepack ratio 0.005 distance 140 radfactor 1.05

geometry set Parcel_2
geometry generate group Parcel box 0 0.32 0 0.22 0.146 0.251
[vol2 = 0.32*0.22*0.105] ;Volume of Parcel_2
[mas2 = 3.2] ;Mass of Parcel_2
[den2 = mas2 / vol2] ;Density of Parcel_2
clump template create name Parcel_2 geometry Parcel_2 surfcalculate ...
    bubblepack ratio 0.005 distance 140 radfactor 1.05

geometry set Parcel_3
geometry generate group Parcel box 0 0.32 0 0.22 0.252 0.357
[vol3 = 0.32*0.22*0.105] ;Volume of Parcel_3
[mas3 = 3.2] ;Mass of Parcel_3
[den3 = mas3 / vol3] ;Density of Parcel_3
clump template create name Parcel_3 geometry Parcel_3 surfcalculate ...
    bubblepack ratio 0.005 distance 140 radfactor 1.05

geometry set Parcel_4
geometry generate group Parcel box 0 0.32 0 0.22 0.358 0.463
[vol4 = 0.32*0.22*0.105] ;Volume of Parcel_4
[mas4 = 3.2] ;Mass of Parcel_4
[den4 = mas4 / vol4] ;Density of Parcel_4
clump template create name Parcel_4 geometry Parcel_4 surfcalculate ...
    bubblepack ratio 0.005 distance 140 radfactor 1.05

clump replicate name Parcel_1 id 1 density @den1 position 0.92 0.7 0.075 axis 0 0 1 angle 0

clump replicate name Parcel_2 id 2 density @den2 position 1.01 0.7 0.1985 axis 0 0 1 angle 90

clump replicate name Parcel_3 id 3 density @den3 position 1.01 0.7 0.3045 axis 0 0 1 angle 90

clump replicate name Parcel_4 id 4 density @den4 position 1.01 0.7 0.4105 axis 0 0 1 angle 90

define Finder
whilestepping

c1 = clump.find(1)
pos1 = clump.pos(c1)
vel1 = clump.vel(c1)

c2 = clump.find(2)
pos2 = clump.pos(c2)
vel2 = clump.vel(c2)

c3 = clump.find(3)
pos3 = clump.pos(c3)
vel3 = clump.vel(c3)

c4 = clump.find(4)
pos4 = clump.pos(c4)
vel4 = clump.vel(c4)

end

@Finder

set gravity 9.81
history id 200 mechanical age

;Setting the ControlBarriers on the UpperConveyorBelts
geometry set ControlBarrier1
[xl = xa1-0.1]
[xu = xa1-.099]
[yl = 0]
[yu = 1.2]
[zl = h + 0.07]
[zu = h + 0.1]
geometry generate box @xl @xu @yl @yu @zl @zu

geometry set ControlBarrier2
[xl2 = xa2 + 0.5 ]
[xu2 = xa2 + 0.5 + 0.001]
[yl2 = 0]
[yu2 = 1.2]
```

```
[zl2 = h+0.07]
[zu2 = h+0.1]
geometry generate box @xl2 @xu2 @yl2 @yu2 @zl2 @zu2

;Setting the ControlFunction in the defined ControlBarriers
define Counter
whilestepping

vl = vector(xl, yl, zl)
vu = vector(xu, yu, zu)

vl2 = vector(xl2, yl2, zl2)
vu2 = vector(xu2, yu2, zu2)

a = clump.inbox(vl, vu)
ar = array.size(a,1)

a2 = clump.inbox(vl2, vu2)
ar2 = array.size(a2,1)

end

@Counter

;Recording the values within the ControlBarriers
history add id 500 fish @ar
history add id 501 fish @ar2

;Setting of the CalmTIME for the system
solve time @CalmTIME calm 500

;Save the initial configuration
[initial = string('initial-state_Versuch')]
[initialstate = string(initial+Versuch)]

save @initialstate

;Output of video material
[n=0]
define Stepping

whilestepping
tcurrent = mech.age
tset = 0.6 ;25 pictures per second 0.04
tcurrent1 = tcurrent - n*tset
nn = string(n)
nrunNumber = string(runNumber)
Moviestep = string(nrunNumber+'_'+nn)

if tcurrent1 > tset

n = n + 1

command
plot bitmap Plot 1 filename @Moviestep
endcommand

endif

end

@Stepping  ;writing file

define Final

nrunNumber = string(runNumber)
Filename = string('Output'+'.txt')

OUT_runNumber  = string(runNumber)
OUT_Variable_DP                    = string(DP)
OUT_DisturbanceVariables_SP        = string(SP)
OUT_DisturbanceVariables_fric1     = string(fric1)
OUT_DisturbanceVariables_fric2     = string(fric2)
OUT_Time                           = string(tcurrent)
OUT_Clump1_PosX                    = string(comp(pos1,1))
OUT_Clump1_PosY                    = string(comp(pos1,2))
OUT_Clump1_PosZ                    = string(comp(pos1,3))
OUT_Clump2_PosX                    = string(comp(pos2,1))
```

```
OUT_Clump2_PosY                    = string(comp(pos2,2))
OUT_Clump2_PosZ                    = string(comp(pos2,3))
OUT_Clump3_PosX                    = string(comp(pos3,1))
OUT_Clump3_PosY                    = string(comp(pos3,2))
OUT_Clump3_PosZ                    = string(comp(pos3,3))
OUT_Clump4_PosX                    = string(comp(pos4,1))
OUT_Clump4_PosY                    = string(comp(pos4,2))
OUT_Clump4_PosZ                    = string(comp(pos4,3))

Outputstring  = string(...
    OUT_runNumber + '\t' + ...
    OUT_Variable_DP + '\t' + ...
    OUT_DisturbanceVariables_SP + '\t' + ...
    OUT_DisturbanceVariables_fric1 + '\t' + ...
    OUT_DisturbanceVariables_fric2 + '\t' + ...
    OUT_Time + '\t' + ...
    OUT_Clump1_PosX + '\t' + ...
    OUT_Clump1_PosY + '\t' + ...
    OUT_Clump1_PosZ + '\t' + ...
    OUT_Clump2_PosX + '\t' + ...
    OUT_Clump2_PosY + '\t' + ...
    OUT_Clump2_PosZ + '\t' + ...
    OUT_Clump3_PosX + '\t' + ...
    OUT_Clump3_PosY + '\t' + ...
    OUT_Clump3_PosZ + '\t' + ...
    OUT_Clump4_PosX + '\t' + ...
    OUT_Clump4_PosY + '\t' + ...
    OUT_Clump4_PosZ)

array Output(1)
Output(1) = Outputstring

out1 = file.open(Filename,2,1)
out1 = file.write(Output,1)
out1 = file.close

end

;Set the ConveyorBeltSpeed, including ConveyingSpeedRamp
define Rampe
whilestepping
k_rampe = v2x / t_rampe
v_rampe = (tcurrent - CalmTIME) * k_rampe

if v_rampe > v2x
v_rampe = v2x
else if v_rampe < 0
v_rampe = 0
endif

end

wall attribute conveyor @v1ax @v1ay 0 range id 1
wall attribute conveyor @v1bx @v1by 0 range id 2
wall attribute conveyor @v2x 0 0 range id 3


;solve time @t_rampe

;[Rem_TIME = TIME - 0.05- t_rampe] ;Remaining time minus Calmtime - ConveyingSpeedRamp

;Setting the simulation time

solve time @TIME

@Final   ;writing file

[ends = string('end-state_Versuch')]
[endstate = string(ends+Versuch)]
[Plot = string('Vereinzelung_Versuch')]
[Plotstring = string(Plot+Versuch)]

;plot bitmap Plot 2 filename @Plotstring

save @endstate
```

8.2.2 Program Code PFC3D- Parameter

```
title 'Parameter'

;Simparameter
[k1 = 1] ;Poisson's ratio

;Variables
[Versuch = string(1)]
[TIME = 1.8] ;test period
[CalmTIME = 0.02] ;settling time

[c2x = 1.0] ;Belt length above
[v2x = 0.25] ;Velocity of UpperConveyorBelt

[h = -0.45] ;Waterfall height

[c1x = 2] ;Belt length below

[v1a= 0.0] ;Velocity of LowerConveyorBeltLeft a
[alpha1a= -30] ;Angle of LowerConveyorBeltLeft a
[v1b= 0.0] ;Velocity of LowerConveyorBeltRight b
[alpha1b= 30] ;Angle of LowerConveyorBeltRight b

[v1ax = math.cos(alpha1a/180*math.pi)*v1a] ;velocity component x of LowerConveyorBeltLeft a
[v1ay = math.sin(alpha1a/180*math.pi)*v1a] ;velocity component y of LowerConveyorBeltLeft a
[v1bx = math.cos(alpha1b/180*math.pi)*v1b] ;velocity component x of LowerConveyorBeltRight b
[v1by = math.sin(alpha1b/180*math.pi)*v1b] ;velocity component y of LowerConveyorBeltRight b

[la1 = 0.6] ;Length of Deflector1
[la2 = la1] ;Length of Deflector2
[xa1 = c2x+0.8] ;Distance X Deflector1
[xa2 = xa1+0.4] ;Distance X Deflector2
[alpha = 45.] ;Angle of Deflector1
[betha = -45.] ;Angle of Deflector2

[t_rampe = 0.5] ;Time to the final speed

[DP = 0.9] ;Damping Coefficient

;DisturbanceVariables
[var1 = 1] ;Shear Modulus
[var2 = 1] ;Coefficient of friction between parcel-parcel
[var3 = 1] ;Coefficient of friction between parcel-ground

define SetDisturbanceVariables
array DisturbanceVariables(3,4)

;Shear Modulus
DisturbanceVariables(1,1) = 1e9
DisturbanceVariables(1,2) = 5e9
DisturbanceVariables(1,3) = 1e10
DisturbanceVariables(1,4) = 5e10

;Coefficient of friction between parcel-parcel
DisturbanceVariables(2,1) = 0.2
DisturbanceVariables(2,2) = 0.3
DisturbanceVariables(2,3) = 0.4
DisturbanceVariables(2,4) = 0.5

;Coefficient of friction between parcel-ground
DisturbanceVariables(3,1) = 0.4
DisturbanceVariables(3,2) = 0.7
DisturbanceVariables(3,3) = 1.0
DisturbanceVariables(3,4) = 1.3

end

;Simparameter
define Simparameter
array config(1,2)

config(1,1) = 0.2      ;Poisson's ratio Parcel 0
config(1,2) = 0.4      ;Poisson's ratio Parcel 1

end
```

8.2.3 Program Code PFC3D- Run

```
title 'run'
```

Table 15: PFC3D-run code

```
new     ;Run 1          new     ;Run 2          new     ;Run 3          new     ;Run 4
call Parameter          call Parameter          call Parameter          call Parameter
[runNumber  = 1]        [runNumber  = 2]        [runNumber  = 3]        [runNumber  = 4]
[var1  = 1]             [var1  = 2]             [var1  = 3]             [var1  = 4]
[var2  = 1]             [var2  = 1]             [var2  = 1]             [var2  = 1]
[var3  = 1]             [var3  = 1]             [var3  = 1]             [var3  = 1]
Call Base               Call Base               Call Base               Call Base
```

```
new     ;Run 5          new     ;Run 6          new     ;Run 7          new     ;Run 8
call Parameter          call Parameter          call Parameter          call Parameter
[runNumber  = 5]        [runNumber  = 6]        [runNumber  = 7]        [runNumber  = 8]
[var1  = 1]             [var1  = 2]             [var1  = 3]             [var1  = 4]
[var2  = 2]             [var2  = 2]             [var2  = 2]             [var2  = 2]
[var3  = 1]             [var3  = 1]             [var3  = 1]             [var3  = 1]
Call Base               Call Base               Call Base               Call Base
```

```
new     ;Run 9          new     ;Run 10         new     ;Run 11         new     ;Run 12
call Parameter          call Parameter          call Parameter          call Parameter
[runNumber  = 9]        [runNumber  = 10]       [runNumber  = 11]       [runNumber  = 12]
[var1  = 1]             [var1  = 2]             [var1  = 3]             [var1  = 4]
[var2  = 3]             [var2  = 3]             [var2  = 3]             [var2  = 3]
[var3  = 1]             [var3  = 1]             [var3  = 1]             [var3  = 1]
Call Base               Call Base               Call Base               Call Base
```

```
new     ;Run 13         new     ;Run 14         new     ;Run 15         new     ;Run 16
call Parameter          call Parameter          call Parameter          call Parameter
[runNumber  = 13]       [runNumber  = 14]       [runNumber  = 15]       [runNumber  = 16]
[var1  = 1]             [var1  = 2]             [var1  = 3]             [var1  = 4]
[var2  = 4]             [var2  = 4]             [var2  = 4]             [var2  = 4]
[var3  = 1]             [var3  = 1]             [var3  = 1]             [var3  = 1]
Call Base               Call Base               Call Base               Call Base
```

```
new     ;Run 17         new     ;Run 18         new     ;Run 19         new     ;Run 20
call Parameter          call Parameter          call Parameter          call Parameter
[runNumber  = 17]       [runNumber  = 18]       [runNumber  = 19]       [runNumber  = 20]
[var1  = 1]             [var1  = 2]             [var1  = 3]             [var1  = 4]
[var2  = 1]             [var2  = 1]             [var2  = 1]             [var2  = 1]
[var3  = 2]             [var3  = 2]             [var3  = 2]             [var3  = 2]
Call Base               Call Base               Call Base               Call Base
```

new ;Run 21 call Parameter [runNumber = 21] [var1 = 1] [var2 = 2] [var3 = 2] Call Base	**new** ;Run 22 call Parameter [runNumber = 22] [var1 = 2] [var2 = 2] [var3 = 2] Call Base	**new** ;Run 23 call Parameter [runNumber = 23] [var1 = 3] [var2 = 2] [var3 = 2] Call Base	**new** ;Run 24 call Parameter [runNumber = 24] [var1 = 4] [var2 = 2] [var3 = 2] Call Base
new ;Run 25 call Parameter [runNumber = 25] [var1 = 1] [var2 = 3] [var3 = 2] Call Base	**new** ;Run 26 call Parameter [runNumber = 26] [var1 = 2] [var2 = 3] [var3 = 2] Call Base	**new** ;Run 27 call Parameter [runNumber = 27] [var1 = 3] [var2 = 3] [var3 = 2] Call Base	**new** ;Run 28 call Parameter [runNumber = 28] [var1 = 4] [var2 = 3] [var3 = 2] Call Base
new ;Run 29 call Parameter [runNumber = 29] [var1 = 1] [var2 = 4] [var3 = 2] Call Base	**new** ;Run 30 call Parameter [runNumber = 30] [var1 = 2] [var2 = 4] [var3 = 2] Call Base	**new** ;Run 31 call Parameter [runNumber = 31] [var1 = 3] [var2 = 4] [var3 = 2] Call Base	**new** ;Run 32 call Parameter [runNumber = 32] [var1 = 4] [var2 = 4] [var3 = 2] Call Base
new ;Run 33 call Parameter [runNumber = 33] [var1 = 1] [var2 = 1] [var3 = 3] Call Base	**new** ;Run 34 call Parameter [runNumber = 34] [var1 = 2] [var2 = 1] [var3 = 3] Call Base	**new** ;Run 35 call Parameter [runNumber = 35] [var1 = 3] [var2 = 1] [var3 = 3] Call Base	**new** ;Run 36 call Parameter [runNumber = 36] [var1 = 4] [var2 = 1] [var3 = 3] Call Base
new ;Run 37 call Parameter [runNumber = 37] [var1 = 1] [var2 = 2] [var3 = 3] Call Base	**new** ;Run 38 call Parameter [runNumber = 38] [var1 = 2] [var2 = 2] [var3 = 3] Call Base	**new** ;Run 39 call Parameter [runNumber = 39] [var1 = 3] [var2 = 2] [var3 = 3] Call Base	**new** ;Run 40 call Parameter [runNumber = 40] [var1 = 4] [var2 = 2] [var3 = 3] Call Base
new ;Run 41 call Parameter [runNumber = 41] [var1 = 1] [var2 = 3] [var3 = 3] Call Base	**new** ;Run 42 call Parameter [runNumber = 42] [var1 = 2] [var2 = 3] [var3 = 3] Call Base	**new** ;Run 43 call Parameter [runNumber = 43] [var1 = 3] [var2 = 3] [var3 = 3] Call Base	**new** ;Run 44 call Parameter [runNumber = 44] [var1 = 4] [var2 = 3] [var3 = 3] Call Base

new ;Run 45 call Parameter **[**runNumber **= 45]** **[**var1 **= 1]** **[**var2 **= 4]** **[**var3 **= 3]** Call Base	**new** ;Run 46 call Parameter **[**runNumber **= 46]** **[**var1 **= 2]** **[**var2 **= 4]** **[**var3 **= 3]** Call Base	**new** ;Run 47 call Parameter **[**runNumber **= 47]** **[**var1 **= 3]** **[**var2 **= 4]** **[**var3 **= 3]** Call Base	**new** ;Run 48 call Parameter **[**runNumber **= 48]** **[**var1 **= 4]** **[**var2 **= 4]** **[**var3 **= 3]** Call Base
new ;Run 49 call Parameter **[**runNumber **= 49]** **[**var1 **= 1]** **[**var2 **= 1]** **[**var3 **= 4]** Call Base	**new** ;Run 50 call Parameter **[**runNumber **= 50]** **[**var1 **= 2]** **[**var2 **= 1]** **[**var3 **= 4]** Call Base	**new** ;Run 51 call Parameter **[**runNumber **= 51]** **[**var1 **= 3]** **[**var2 **= 1]** **[**var3 **= 4]** Call Base	**new** ;Run 52 call Parameter **[**runNumber **= 52]** **[**var1 **= 4]** **[**var2 **= 1]** **[**var3 **= 4]** Call Base
new ;Run 53 call Parameter **[**runNumber **= 53]** **[**var1 **= 1]** **[**var2 **= 2]** **[**var3 **= 4]** Call Base	**new** ;Run 54 call Parameter **[**runNumber **= 54]** **[**var1 **= 2]** **[**var2 **= 2]** **[**var3 **= 4]** Call Base	**new** ;Run 55 call Parameter **[**runNumber **= 55]** **[**var1 **= 3]** **[**var2 **= 2]** **[**var3 **= 4]** Call Base	**new** ;Run 56 call Parameter **[**runNumber **= 56]** **[**var1 **= 4]** **[**var2 **= 2]** **[**var3 **= 4]** Call Base
new ;Run 57 call Parameter **[**runNumber **= 57]** **[**var1 **= 1]** **[**var2 **= 3]** **[**var3 **= 4]** Call Base	**new** ;Run 58 call Parameter **[**runNumber **= 58]** **[**var1 **= 2]** **[**var2 **= 3]** **[**var3 **= 4]** Call Base	**new** ;Run 59 call Parameter **[**runNumber **= 59]** **[**var1 **= 3]** **[**var2 **= 3]** **[**var3 **= 4]** Call Base	**new** ;Run 60 call Parameter **[**runNumber **= 60]** **[**var1 **= 4]** **[**var2 **= 3]** **[**var3 **= 4]** Call Base
new ;Run 61 call Parameter **[**runNumber **= 61]** **[**var1 **= 1]** **[**var2 **= 4]** **[**var3 **= 4]** Call Base	**new** ;Run 62 call Parameter **[**runNumber **= 62]** **[**var1 **= 2]** **[**var2 **= 4]** **[**var3 **= 4]** Call Base	**new** ;Run 63 call Parameter **[**runNumber **= 63]** **[**var1 **= 3]** **[**var2 **= 4]** **[**var3 **= 4]** Call Base	**new** ;Run 64 call Parameter **[**runNumber **= 64]** **[**var1 **= 4]** **[**var2 **= 4]** **[**var3 **= 4]** Call Base

8.2.4 DoE-Experimental Investigation with Real Attempts

Table 16: Table of real attempts

Run	clump 1			clump 2			clump 3			clump 4		
	PosX1	PosY1	PosZ1	PosX2	PosY2	PosZ2	Posx3	PosY3	PosZ3	PosX4	PosY4	PosZ4
1	1,270	0,651	-0,307	1,435	0,674	-0,363	1,662	0,675	-0,3975	1,890	0,692	-0,3975
2	1,270	0,655	-0,291	1,429	0,670	-0,341	1,621	0,666	-0,3975	1,845	0,667	-0,3975
3	1,285	0,673	-0,299	1,443	0,684	-0,346	1,654	0,674	-0,3975	1,881	0,673	-0,3975
4	1,271	0,670	-0,292	1,415	0,679	-0,347	1,620	0,672	-0,3975	1,849	0,671	-0,3975
5	1,272	0,687	-0,300	1,425	0,694	-0,345	1,633	0,695	-0,3975	1,859	0,693	-0,3975
6	1,279	0,670	-0,298	1,423	0,669	-0,351	1,639	0,670	-0,3975	1,869	0,671	-0,3975
7	1,284	0,685	-0,299	1,438	0,664	-0,352	1,647	0,680	-0,3975	1,871	0,680	-0,3975
8	1,253	0,680	-0,301	1,411	0,691	-0,344	1,623	0,687	-0,3975	1,857	0,690	-0,3975
9	1,289	0,684	-0,302	1,444	0,689	-0,349	1,651	0,694	-0,3975	1,871	0,695	-0,3975
10	1,291	0,678	-0,303	1,448	0,684	-0,353	1,664	0,688	-0,3975	1,891	0,697	-0,3975
arithmetic mean	1,2764	0,6733	-0,2992	1,4311	0,6798	-0,3491	1,6414	0,6801	-0,3975	1,8683	0,6829	-0,3975
standard deviation	0,0115	0,0123	0,0048	0,0126	0,0102	0,0062	0,0167	0,0103	0,0000	0,0160	0,0117	0,0000

8.2.5 Position Offset Analysis

Table 17: Offset-analysis between experimental setup and simulation model

offset clump 1	offset clump 2	offset clump 3	offset clump 4
0,16368	0,10577	0,10354	0,09042
0,15794	0,15671	0,14456	0,13569
0,17964	0,15193	0,13770	0,12628
0,23470	0,06252	0,05649	0,06926
0,06901	0,07990	0,09393	0,07013
0,12336	0,14255	0,13287	0,12345
0,14456	0,09810	0,10219	0,08906
0,10738	0,12022	0,10756	0,09460
0,18580	0,14335	0,13461	0,12460
0,15495	0,16854	0,16454	0,15683
0,15421	0,13770	0,13184	0,12175
0,10014	0,09609	0,07658	0,08815
0,17823	0,14453	0,13875	0,12970
0,18539	0,15883	0,14635	0,13790
0,09958	0,10036	0,10311	0,08971
0,28316	0,10166	0,06669	0,05772
0,13472	0,15544	0,15115	0,14150
0,15178	0,18035	0,16416	0,15663
0,15639	0,14856	0,13153	0,12089
0,06697	0,08768	0,08254	0,06219
0,16148	0,13944	0,11712	0,10467
0,16694	0,14322	0,12890	0,11914
0,08282	0,09542	0,11822	0,10009
0,11668	0,14668	0,13562	0,12622
0,11377	0,14984	0,15022	0,14023
0,13576	0,16293	0,16804	0,15999
0,13207	0,14110	0,12324	0,11026
0,24783	0,10706	0,05903	0,05125
0,11979	0,14055	0,14373	0,13509
0,11724	0,09462	0,09319	0,07697
0,12626	0,15833	0,16981	0,16221
0,27999	0,08471	0,10199	0,09881
0,16368	0,10577	0,10354	0,09042
0,15794	0,15671	0,14456	0,13569
0,17964	0,15193	0,13770	0,12628
0,23470	0,06252	0,05649	0,06926
0,06901	0,07990	0,09393	0,07013
0,12336	0,14255	0,13287	0,12345
0,14456	0,09810	0,10219	0,08906
0,10738	0,12022	0,10756	0,09460
0,18580	0,14335	0,13461	0,12460
0,15495	0,16854	0,16454	0,15683
0,15421	0,13770	0,13184	0,12175
0,10014	0,09609	0,07658	0,08815
0,17823	0,14453	0,13875	0,12970
0,18539	0,15883	0,14635	0,13790
0,09958	0,10036	0,10311	0,08971
0,28316	0,10166	0,06669	0,05772
0,13472	0,15544	0,15115	0,14150
0,15178	0,18035	0,16416	0,15663
0,15639	0,14856	0,13153	0,12089
0,06697	0,08768	0,08254	0,06219
0,16148	0,13944	0,11712	0,10467
0,16694	0,14322	0,12890	0,11914
0,08282	0,09542	0,11822	0,10009
0,11668	0,14668	0,13562	0,12622
0,11377	0,14984	0,15022	0,14023
0,13576	0,16293	0,16804	0,15999
0,13207	0,14110	0,12324	0,11026
0,24783	0,10706	0,05903	0,05125
0,11979	0,14055	0,14373	0,13509
0,11724	0,09462	0,09319	0,07697
0,12626	0,15833	0,16981	0,16221
0,27999	0,08471	0,10199	0,09881

8.2.6 Artificial Neural Network

Table 18: Input matrix for ANN

Run	SP (Shear Modulus)	fric1 (parcel-parcel)	fric2 (parcel-ground)
1	1,E+09	0,2	0,4
2	5,E+09	0,2	0,4
3	1,E+10	0,2	0,4
4	5,E+10	0,2	0,4
5	1,E+09	0,3	0,4
6	5,E+09	0,3	0,4
7	1,E+10	0,3	0,4
8	5,E+10	0,3	0,4
9	1,E+09	0,4	0,4
10	5,E+09	0,4	0,4
11	1,E+10	0,4	0,4
12	5,E+10	0,4	0,4
13	1,E+09	0,5	0,4
14	5,E+09	0,5	0,4
15	1,E+10	0,5	0,4
16	5,E+10	0,5	0,4
17	1,E+09	0,2	0,7
18	5,E+09	0,2	0,7
19	1,E+10	0,2	0,7
20	5,E+10	0,2	0,7
21	1,E+09	0,3	0,7
22	5,E+09	0,3	0,7
23	1,E+10	0,3	0,7
24	5,E+10	0,3	0,7
25	1,E+09	0,4	0,7
26	5,E+09	0,4	0,7
27	1,E+10	0,4	0,7
28	5,E+10	0,4	0,7
29	1,E+09	0,5	0,7
30	5,E+09	0,5	0,7
31	1,E+10	0,5	0,7
32	5,E+10	0,5	0,7
33	1,E+09	0,2	1
34	5,E+09	0,2	1
35	1,E+10	0,2	1
36	5,E+10	0,2	1
37	1,E+09	0,3	1
38	5,E+09	0,3	1
39	1,E+10	0,3	1
40	5,E+10	0,3	1
41	1,E+09	0,4	1
42	5,E+09	0,4	1
43	1,E+10	0,4	1
44	5,E+10	0,4	1
45	1,E+09	0,5	1
46	5,E+09	0,5	1
47	1,E+10	0,5	1
48	5,E+10	0,5	1
49	1,E+09	0,2	1,3
50	5,E+09	0,2	1,3
51	1,E+10	0,2	1,3
52	5,E+10	0,2	1,3
53	1,E+09	0,3	1,3
54	5,E+09	0,3	1,3
55	1,E+10	0,3	1,3
56	5,E+10	0,3	1,3
57	1,E+09	0,4	1,3
58	5,E+09	0,4	1,3
59	1,E+10	0,4	1,3
60	5,E+10	0,4	1,3
61	1,E+09	0,5	1,3
62	5,E+09	0,5	1,3
63	1,E+10	0,5	1,3
64	5,E+10	0,5	1,3

Table 19: Target matrix for ANN

clump 1			clump 2			clump 3			clump 4		
PosX	PosY	PosZ	PosX	PosY	PosZ	Posx	PosY	PosZ	PosX	PosY	PosZ
1,13699	0,741999	-0,247852	1,36921	0,745024	-0,339542	1,47967	0,709061	-0,339542	1,73106	0,751486	-0,336399
1,14953	0,752494	-0,248434	1,30577	0,730924	-0,339529	1,76802	0,625861	-0,291316	1,84882	0,633575	-0,396735
1,12442	0,750325	-0,24227	1,31316	0,722363	-0,334086	1,662	0,652702	-0,334201	1,91947	0,700388	-0,396734
1,50743	0,705603	-0,27344	1,47802	0,69787	-0,396736	1,87003	0,717832	-0,290966	1,89606	0,710923	-0,396735
1,28489	0,694227	-0,233992	1,38994	0,733427	-0,330458	1,6178	0,677063	-0,333331	1,88248	0,717671	-0,396734
1,20558	0,761028	-0,249141	1,33051	0,750729	-0,339542	1,49346	0,686593	-0,339519	1,76196	0,689944	-0,396734
1,14124	0,668077	-0,248181	1,34747	0,708889	-0,339541	1,51344	0,724345	-0,339514	1,64952	0,703808	-0,339331
1,20433	0,732978	-0,246514	1,34101	0,705814	-0,336586	1,51872	0,686394	-0,339544	1,68257	0,653149	-0,339541
1,11048	0,738922	-0,24739	1,31466	0,723115	-0,339513	1,55913	0,811774	-0,390487	1,89262	0,704169	-0,396734
1,14942	0,745945	-0,248142	1,28785	0,742613	-0,337713	1,43036	0,714118	-0,335763	1,61272	0,702067	-0,263655
1,14607	0,736136	-0,245845	1,3208	0,728474	-0,332169	1,83658	0,721599	-0,291373	1,90314	0,720463	-0,396735
1,35551	0,614421	-0,28178	1,50501	0,669911	-0,396112	1,84168	0,71564	-0,291002	1,85272	0,727506	-0,396735
1,12125	0,745237	-0,248988	1,31624	0,739281	-0,339542	1,51857	0,701037	-0,339536	1,60779	0,779248	-0,33928
1,11887	0,757319	-0,249238	1,30591	0,736796	-0,339344	1,48164	0,70183	-0,339544	1,66164	0,780381	-0,338448
1,20622	0,719512	-0,24577	1,35981	0,731718	-0,332659	1,64884	0,632695	-0,396734	2,50508	0,621275	-0,396734
1,54328	0,757081	-0,255209	1,46824	0,713453	-0,377723	1,92895	0,727978	-0,290939	1,94086	0,734496	-0,396735
1,16668	0,729484	-0,244853	1,29675	0,72273	-0,337744	1,5752	0,648883	-0,344333	1,90208	0,707487	-0,396734
1,15654	0,751787	-0,249105	1,27664	0,703935	-0,339541	1,49612	0,670886	-0,339474	1,68091	0,636794	-0,33935
1,15902	0,762193	-0,246497	1,32437	0,735769	-0,339534	1,4919	0,645283	-0,339542	1,63465	0,712824	-0,339542
1,29003	0,707274	-0,243123	1,37289	0,696506	-0,334974	1,60222	0,88246	-0,330231	1,89513	0,822359	-0,396734
1,15733	0,768404	-0,245798	1,34422	0,73739	-0,339541	1,50249	0,674845	-0,3383	1,8026	0,904808	-0,396734
1,14269	0,759734	-0,248994	1,32853	0,739587	-0,339111	1,48348	0,704565	-0,337232	1,66274	0,565988	-0,284388
1,31206	0,711597	-0,235005	1,37179	0,7594	-0,336285	1,47676	0,953692	-0,331445	1,59452	1,05281	-0,307307
1,1874	0,729328	-0,248663	1,30531	0,675964	-0,33945	1,79979	0,701138	-0,294048	1,93194	0,688896	-0,396735
1,17719	0,678205	-0,243728	1,29199	0,691542	-0,335903	1,66943	0,710015	-0,346259	1,9504	0,753123	-0,396734
1,16265	0,725854	-0,246943	1,286	0,746519	-0,339541	1,54728	0,784439	-0,339525	1,88494	0,662361	-0,299322
1,19947	0,764967	-0,243341	1,33952	0,740463	-0,339539	1,49124	0,688604	-0,338707	1,89264	0,699218	-0,396734
1,50054	0,77083	-0,258352	1,44789	0,71896	-0,377576	1,86757	0,692837	-0,247545	1,93878	0,696932	-0,396735
1,16951	0,693884	-0,249192	1,30137	0,716236	-0,339535	1,5718	0,614582	-0,33786	1,77001	0,714754	-0,337072
1,17333	0,689669	-0,245782	1,35474	0,679912	-0,339446	1,46594	0,659161	-0,339462	1,67994	0,999303	-0,326831
1,161	0,674726	-0,247983	1,28129	0,741194	-0,339036	1,49769	0,522751	-0,338758	1,69273	0,714246	-0,396734
1,54368	0,736968	-0,245318	1,44592	0,76512	-0,396684	1,91171	0,801121	-0,291446	1,96715	0,740995	-0,396735
1,13699	0,741999	-0,247852	1,36921	0,745024	-0,339542	1,47967	0,709061	-0,339542	1,73106	0,751486	-0,336399
1,14953	0,752494	-0,248434	1,30577	0,730924	-0,339529	1,76802	0,625861	-0,291316	1,84882	0,633575	-0,396735
1,12442	0,750325	-0,24227	1,31316	0,722363	-0,334086	1,662	0,652702	-0,334201	1,91947	0,700388	-0,396734
1,50743	0,705603	-0,27344	1,47802	0,69787	-0,396736	1,87003	0,717832	-0,290966	1,89606	0,710923	-0,396735
1,28489	0,694227	-0,233992	1,38994	0,733427	-0,330458	1,6178	0,677063	-0,333331	1,88248	0,717671	-0,396734
1,20558	0,761028	-0,249141	1,33051	0,750729	-0,339542	1,49346	0,686593	-0,339519	1,76196	0,689944	-0,396734
1,14124	0,668077	-0,248181	1,34747	0,708889	-0,339541	1,51344	0,724345	-0,339514	1,64952	0,703808	-0,339331
1,20433	0,732978	-0,246514	1,34101	0,705814	-0,336586	1,51872	0,686394	-0,339544	1,68257	0,653149	-0,339541
1,11048	0,738922	-0,24739	1,31466	0,723115	-0,339513	1,55913	0,811774	-0,390487	1,89262	0,704169	-0,396734
1,14942	0,745945	-0,248142	1,28785	0,742613	-0,337713	1,43036	0,714118	-0,335763	1,61272	0,702067	-0,263655
1,14607	0,736136	-0,245845	1,3208	0,728474	-0,332169	1,83658	0,721599	-0,291373	1,90314	0,720463	-0,396735
1,35551	0,614421	-0,28178	1,50501	0,669911	-0,396112	1,84168	0,71564	-0,291002	1,85272	0,727506	-0,396735
1,12125	0,745237	-0,248988	1,31624	0,739281	-0,339542	1,51857	0,701037	-0,339536	1,60779	0,779248	-0,33928
1,11887	0,757319	-0,249238	1,30591	0,736796	-0,339344	1,48164	0,70183	-0,339544	1,66164	0,780381	-0,338448
1,20622	0,719512	-0,24577	1,35981	0,731718	-0,332659	1,64884	0,632695	-0,396734	2,50508	0,621275	-0,396734
1,54328	0,757081	-0,255209	1,46824	0,713453	-0,377723	1,92895	0,727978	-0,290939	1,94086	0,734496	-0,396735
1,16668	0,729484	-0,244853	1,29675	0,72273	-0,337744	1,5752	0,648883	-0,344333	1,90208	0,707487	-0,396734
1,15654	0,751787	-0,249105	1,27664	0,703935	-0,339541	1,49612	0,670886	-0,339474	1,68091	0,636794	-0,33935
1,15902	0,762193	-0,246497	1,32437	0,735769	-0,339534	1,4919	0,645283	-0,339542	1,63465	0,712824	-0,339542
1,29003	0,707274	-0,243123	1,37289	0,696506	-0,334974	1,60222	0,88246	-0,330231	1,89513	0,822359	-0,396734
1,15733	0,768404	-0,245798	1,34422	0,73739	-0,339541	1,50249	0,674845	-0,3383	1,8026	0,904808	-0,396734
1,14269	0,759734	-0,248994	1,32853	0,739587	-0,339111	1,48348	0,704565	-0,337232	1,66274	0,565988	-0,284388
1,31206	0,711597	-0,235005	1,37179	0,7594	-0,336285	1,47676	0,953692	-0,331445	1,59452	1,05281	-0,307307
1,1874	0,729328	-0,248663	1,30531	0,675964	-0,33945	1,79979	0,701138	-0,294048	1,93194	0,688896	-0,396735
1,17719	0,678205	-0,243728	1,29199	0,691542	-0,335903	1,66943	0,710015	-0,346259	1,9504	0,753123	-0,396734
1,16265	0,725854	-0,246943	1,286	0,746519	-0,339541	1,54728	0,784439	-0,339525	1,88494	0,662361	-0,299322
1,19947	0,764967	-0,243341	1,33952	0,740463	-0,339539	1,49124	0,688604	-0,338707	1,89264	0,699218	-0,396734
1,50054	0,77083	-0,258352	1,44789	0,71896	-0,377576	1,86757	0,692837	-0,247545	1,93878	0,696932	-0,396735
1,16951	0,693884	-0,249192	1,30137	0,716236	-0,339535	1,5718	0,614582	-0,33786	1,77001	0,714754	-0,337072
1,17333	0,689669	-0,245782	1,35474	0,679912	-0,339446	1,46594	0,659161	-0,339462	1,67994	0,999303	-0,326831
1,161	0,674726	-0,247983	1,28129	0,741194	-0,339036	1,49769	0,522751	-0,338758	1,69273	0,714246	-0,396734
1,54368	0,736968	-0,245318	1,44592	0,76512	-0,396684	1,91171	0,801121	-0,291446	1,96715	0,740995	-0,396735

Table 20: Output matrix from ANN

clump 1			clump 2			clump 3			clump 4		
PosX	PosY	PosZ	PosX	PosY	PosZ	Posx	PosY	PosZ	PosX	PosY	PosZ
1,16223	0,75953	-0,24629	1,31477	0,72785	-0,33361	1,57124	0,67762	-0,32825	1,82748	0,63584	-0,37120
1,16166	0,75067	-0,24821	1,32375	0,73011	-0,33449	1,55075	0,69192	-0,33290	1,80026	0,67286	-0,37095
1,16469	0,74154	-0,24992	1,33308	0,73112	-0,33495	1,53549	0,70720	-0,33681	1,78186	0,70850	-0,37083
1,34611	0,69597	-0,26375	1,43132	0,66469	-0,31899	1,81987	0,75384	-0,33275	1,89702	0,71662	-0,40434
1,15337	0,74015	-0,25017	1,33145	0,73519	-0,33574	1,52543	0,70792	-0,33950	1,75741	0,71914	-0,36930
1,15316	0,73843	-0,25062	1,33348	0,73545	-0,33600	1,52048	0,70959	-0,34035	1,75353	0,72577	-0,37005
1,15320	0,73648	-0,25079	1,33486	0,73511	-0,33604	1,51947	0,71012	-0,34079	1,75531	0,73063	-0,37134
1,28858	0,67665	-0,25244	1,41089	0,67909	-0,32723	1,78128	0,72999	-0,32753	1,94794	0,75514	-0,40374
1,15233	0,73610	-0,25097	1,33622	0,73685	-0,33664	1,51650	0,71321	-0,34198	1,73773	0,73558	-0,36847
1,15324	0,73619	-0,25089	1,33668	0,73625	-0,33675	1,51523	0,71127	-0,34160	1,74087	0,73440	-0,37006
1,15371	0,73526	-0,25048	1,33717	0,73496	-0,33689	1,51713	0,70703	-0,34101	1,74554	0,73259	-0,37275
1,23909	0,68894	-0,24260	1,38183	0,69345	-0,33571	1,71494	0,67193	-0,32408	1,96415	0,72880	-0,41613
1,18460	0,74161	-0,24851	1,34976	0,73733	-0,34155	1,50811	0,71064	-0,33928	1,73062	0,73302	-0,36985
1,19397	0,74329	-0,24747	1,35266	0,73594	-0,34260	1,50463	0,70658	-0,33752	1,73551	0,72948	-0,37319
1,20578	0,74377	-0,24566	1,35784	0,73321	-0,34445	1,50331	0,69707	-0,33515	1,73503	0,72417	-0,37884
1,30295	0,72956	-0,22790	1,38891	0,70444	-0,35406	1,64232	0,61332	-0,31115	1,98858	0,67083	-0,43544
1,17962	0,78224	-0,24280	1,29697	0,71236	-0,33429	1,60389	0,64077	-0,31228	1,82885	0,52627	-0,37040
1,19421	0,76933	-0,24545	1,31159	0,71036	-0,33410	1,58146	0,66510	-0,31564	1,83883	0,57643	-0,37470
1,21624	0,74519	-0,24890	1,33147	0,70689	-0,33225	1,57077	0,70844	-0,32105	1,88684	0,65969	-0,37956
1,30532	0,70260	-0,26090	1,39965	0,68370	-0,33374	1,86300	0,75483	-0,31341	1,85160	0,68298	-0,38137
1,14279	0,74933	-0,24917	1,32145	0,73290	-0,33712	1,57209	0,68152	-0,33579	1,73914	0,65451	-0,35982
1,14640	0,74262	-0,25006	1,32335	0,73187	-0,33586	1,56024	0,69211	-0,33672	1,78886	0,68283	-0,36825
1,14853	0,73184	-0,25007	1,31833	0,72899	-0,33193	1,58330	0,70449	-0,33641	1,92023	0,71057	-0,37953
1,28273	0,68401	-0,24871	1,40182	0,69860	-0,33961	1,93447	0,73972	-0,30728	1,92149	0,70054	-0,36507
1,12802	0,72933	-0,25358	1,34211	0,74383	-0,34061	1,56085	0,70339	-0,34963	1,67398	0,72318	-0,35090
1,13376	0,73002	-0,25196	1,33204	0,73980	-0,33725	1,57404	0,70155	-0,34506	1,79646	0,72045	-0,36449
1,13302	0,72655	-0,24906	1,31109	0,73470	-0,33081	1,62921	0,69839	-0,33920	2,02341	0,71503	-0,38272
1,34745	0,69107	-0,23770	1,42621	0,69991	-0,34913	1,88333	0,72325	-0,30165	1,97929	0,71484	-0,37808
1,19612	0,73829	-0,24918	1,37714	0,74941	-0,35326	1,56630	0,69730	-0,34719	1,67405	0,71935	-0,34868
1,21244	0,74216	-0,24535	1,36239	0,74339	-0,34904	1,59518	0,69189	-0,33873	1,86564	0,70682	-0,36811
1,22382	0,74195	-0,23989	1,33641	0,73616	-0,34166	1,66482	0,68564	-0,32862	2,16729	0,69330	-0,39326
1,39655	0,71733	-0,22749	1,43417	0,70167	-0,35936	1,76844	0,67696	-0,29841	2,00927	0,69593	-0,40641
1,18713	0,74728	-0,25640	1,33415	0,69372	-0,35317	1,44566	0,67723	-0,32044	1,36307	0,60199	-0,35382
1,20610	0,74312	-0,25757	1,33349	0,68376	-0,34888	1,47644	0,67514	-0,31481	1,56431	0,59550	-0,37451
1,22048	0,73270	-0,25612	1,31735	0,67308	-0,33990	1,53375	0,68414	-0,30740	1,87948	0,60999	-0,40306
1,25465	0,70927	-0,26381	1,34101	0,69327	-0,34195	1,76392	0,77909	-0,30055	1,92504	0,69964	-0,38733
1,09454	0,74494	-0,25580	1,30664	0,72060	-0,35272	1,51362	0,64091	-0,33482	1,42556	0,59224	-0,34747
1,10407	0,73271	-0,25877	1,30973	0,71364	-0,34922	1,53703	0,64533	-0,33376	1,61949	0,61143	-0,36845
1,13120	0,71057	-0,25998	1,31104	0,70279	-0,34153	1,56538	0,67869	-0,33114	1,88650	0,67470	-0,39485
1,25635	0,69987	-0,25396	1,35647	0,70367	-0,35385	1,78449	0,76000	-0,29236	1,86086	0,70689	-0,37485
1,06848	0,71353	-0,25665	1,32232	0,74518	-0,35058	1,59686	0,67509	-0,35543	1,56327	0,69803	-0,33816
1,06454	0,70976	-0,25874	1,31817	0,74144	-0,34914	1,62405	0,65795	-0,35356	1,74547	0,68569	-0,35897
1,08208	0,70545	-0,25801	1,31142	0,73355	-0,34516	1,64478	0,65872	-0,34752	1,95975	0,69255	-0,38337
1,38643	0,71715	-0,23866	1,41603	0,70554	-0,37164	1,78645	0,73866	-0,27920	1,84740	0,69265	-0,37736
1,17743	0,71517	-0,24576	1,36492	0,75706	-0,35850	1,69193	0,69468	-0,35254	1,80746	0,73531	-0,34033
1,17140	0,71948	-0,24733	1,35927	0,75367	-0,35840	1,72625	0,66244	-0,34986	1,96523	0,69083	-0,35769
1,17894	0,72425	-0,24674	1,35144	0,74820	-0,35678	1,74231	0,64515	-0,34286	2,11462	0,66489	-0,37630
1,43242	0,71931	-0,23136	1,44390	0,70566	-0,37274	1,82096	0,72242	-0,28007	1,89262	0,68757	-0,37875
1,19315	0,68796	-0,24815	1,29582	0,68413	-0,33356	1,64373	0,77742	-0,32085	1,75012	0,74278	-0,35085
1,17804	0,69476	-0,25306	1,29920	0,68220	-0,33605	1,67927	0,73113	-0,31976	1,85377	0,67474	-0,36259
1,16575	0,70598	-0,25864	1,30771	0,68149	-0,34081	1,70012	0,68102	-0,31798	1,90978	0,59844	-0,37216
1,23604	0,71254	-0,26012	1,31846	0,70147	-0,34303	1,81826	0,77656	-0,29294	2,04713	0,67549	-0,37872
1,15187	0,69234	-0,24572	1,26884	0,69180	-0,33242	1,66855	0,75140	-0,32157	1,83266	0,72137	-0,35864
1,15394	0,69287	-0,25235	1,28861	0,68859	-0,33624	1,68111	0,72335	-0,32315	1,88069	0,68304	-0,36619
1,15395	0,69543	-0,26042	1,31492	0,68778	-0,34273	1,66972	0,69154	-0,32637	1,87508	0,64533	-0,37269
1,27933	0,71191	-0,25162	1,34271	0,71228	-0,35749	1,80947	0,77648	-0,28498	2,02923	0,69840	-0,37248
1,13614	0,70813	-0,23927	1,25885	0,71301	-0,34297	1,62839	0,71707	-0,32399	1,83817	0,72155	-0,37028
1,15527	0,70218	-0,24720	1,29629	0,71147	-0,34974	1,60807	0,70753	-0,32927	1,82625	0,72277	-0,37521
1,18638	0,69391	-0,25717	1,34816	0,70956	-0,35884	1,56846	0,70366	-0,33629	1,77654	0,73612	-0,37908
1,38445	0,72988	-0,24163	1,38614	0,71504	-0,37491	1,78033	0,76578	-0,27353	2,00197	0,68929	-0,37565
1,19502	0,70360	-0,23424	1,29970	0,73342	-0,35800	1,55693	0,74260	-0,33180	1,81324	0,82518	-0,37735
1,18950	0,70544	-0,24178	1,32382	0,73443	-0,36477	1,53288	0,71369	-0,33664	1,77455	0,79708	-0,38179
1,19264	0,70892	-0,25090	1,35665	0,73331	-0,37291	1,50458	0,68086	-0,34103	1,72093	0,75847	-0,38584
1,39341	0,72871	-0,24101	1,40466	0,71502	-0,38043	1,75992	0,75186	-0,27532	1,89647	0,68713	-0,37305