TAMPEREEN TEKNILLINEN YLIOPISTO
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EERO ANTTILA

SIMULATION STUDY FOR AN AUTOMATED STORAGE AND RETRIEVAL SYSTEM

Master of Science Thesis

Examiner: Professor Matti Vilkko
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ABSTRACT

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The scope of this work is in simulating an automated storage and retrieval system (AS/RS) and validating that the system works as expected. AS/RSs can be complex systems and development project of an AS/RS can last for several years. Therefore, there is need for a solution that helps the stakeholders to validate that the designed system works as expected. The solution offered in this work is discrete-event simulation of an AS/RS. The simulated example AS/RS consists of stacker cranes moving on aisles, high bay racking, industrial robots, conveyor system, AGV connection, and packing stations. The amount of devices and high capacity requirements make the simulated system complex. The simulated system is under development during the thesis writing process so most of the details about the system functionality are available. However, some uncertainty causing assumptions are required to simulate the AS/RS.

The goal of this work is divided in three research questions. The first research question is concerning the requirements for simulation platform to simulate an AS/RS. The identified requirements are general flexibility and usability requirements; ability to model required devices, warehouse management system, and material flow; and ability to gather the required performance measurements. The second research question deals with the material flow simulations. The material flow simulations present that the example AS/RS can fill the required maximum infeed amounts but outfeed amounts can not be filled. The reason for this is too low capacity of industrial robots. The third research question is about sensitivity analysis. Firstly, the results present that the realized outfeed amounts are sensitive for variation in robot movement times. If times increase, the realized outfeed amounts decrease significantly. Secondly, the realized infeed amounts are slightly sensitive for total delay of stacker cranes. If delay increases, the realized infeed amount drops a bit. Thirdly, the example AS/RS is not sensitive for variation in storage utilization. This is the benefit of random storage strategy.

Based on the results of this work, the industrial robots are the bottleneck of the example AS/RS. On average, the utilization ratios of industrial robots are 97 % during the maximum infeed and outfeed amount simulations. With better routing of the piles, also the rest of the capacity could be utilized that would lead to higher realized infeed and outfeed amounts. However, then the system would be quite unreliable. Based on the results of this work, the industrial robots require more capacity if designed capacity of the system is required to be filled.

TIIVISTELMÄ

EERO ANTTILA: Automaattisen varastointi- ja hakujärjestelmän simulointi
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Työn tavoitteena on automaattisen varastointi- ja hakujärjestelmän (AS/RS) simulointi, ja järjestelmän toiminnan todentaminen. AS/RS-järjestelmät voivat olla kompleksisia, ja niiden kehitysprojektit voivat kestää useita vuosia. Näistä syistä järjestelmän toimintaa tulisi pystyä todentamaan jo suunnitteluvaiheessa. Työssä esitettävä ratkaisu on AS/RS-järjestelmän tapahtumapohjainen simulointi. Simuloitava järjestelmä koostuu hyllystöhisseistä, hissikäytävistä, korkeavarastosta, teollisuusroboteista, kuljetinjärjestelmästä, vihivaunuliitynnästä ja pakkausasemista. Laitteiden määrä ja korkea kapasiteettivaatimus aiheuttavat järjestelmän kompleksisuuden. Työtä tehdessä simuloitavaa järjestelmää suunnitellaan, joten suurin osa järjestelmän yksityiskohdista on tarjolla. Joitain epävarmoja oletuksia kuitenkin tarvitaan järjestelmää mallinnettaessa.

Työn tavoite jaetaan kolmeen tutkimuskysymykseen. Ensimmäisellä kysymyksellä kartoitetaan vaatimuksia simulointiohjelmistolle, jotta AS/RS-järjestelmää voidaan simuloida. Ohjelmiston tulee olla joustava ja mahdollisuus tarvittavien laitteiden, varastonhallintajärjestelmän ja materiaalivirran mallintamiseen sekä suorituskykydatan keräämiseen vaaditaan. Toinen kysymys liittyy materiaalivirtasimulointiin. Tulokset osoittavat, että järjestelmä saavuttaa vaaditun sisäänsyöttökapasiteetin, mutta ulossyötössä kapasiteettiin ei päästä. Syy on se, että teollisuusrobotit aiheuttavat järjestelmässä pullonkaulan. Kolmas kysymys käsittelee herkkyysanalyysiä. Analyysi osoittaa, että toteutuneet ulossyöttömäärät ovat herkkiä robottien liikeaikojen muutokselle. Aikojen kasvaessa määrät laskevat merkittävästi. Toisaalta toteutuneet sisäänsyöttömäärät ovat hieman herkkiä hyllystöhissien liikkeiden väliselle viiveelle. Jos viive kasvaa, määrät laskevat hiukan. Simuloitava järjestelmä ei kuitenkaan ole herkkä varaston täyttöasteen vaihtelulle. Tämä on hyödynnettävän satunnaisen varastointistrategian etu.

Työn tulosten perusteella teollisuusrobotit ovat järjestelmän pullonkaula. Teollisuusrobottien käyttöasteet ovat keskimäärin 97 % maksimisisään- ja maksimiulossyöttösimuloinneissa. Optimoimalla tuotteiden reititystä, myös loppu 3 % kapasiteetista voitaisiin hyödyntää, jolloin sisään- ja ulossyöttömäärät olisivat korkeampia. Tällöin järjestelmä olisi kuitenkin melko epäluotettava. Työn tulosten perusteella teollisuusrobotit tarvitsisivat enemmän kapasiteettia, jotta järjestelmän tavoitekapasiteetti saavutettaisiin.

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Eero Anttila

CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

AGV	Automated guided vehicle
AS/RS	Automated storage and retrieval system
CSV	Comma-separated values
DES	Discrete-event simulation
ERP	Enterprise resource planning system
PLC	Programmable logic controller
RQ	Research question
WMS	Warehouse management system
XLS	Microsoft Excel spreadsheet

i	Index for event in discrete-event simulation
I	Value of input variable in sensitivity analysis
T_b	The time that a device is busy during simulation
T_S	Simulated time
x	The amount how much input variable is changed in sensitivity analysis

ρ	Device utilization ratio
$\hat{\rho}$	Approximation of device utilization ratio

1. INTRODUCTION

An automated storage and retrieval system (AS/RS) is a system that is used for storing products. Products can be stored e.g. individually, on pallets, or in boxes. A typical AS/RS consists of one or several aisles with two high bay racks by the both sides of the aisles. Automated stacker crane moves along an aisle and it makes storages and retrievals. [1; 2] An example of an AS/RS with three stacker cranes, three aisles, and four high bay racks is in Figure 1.1.

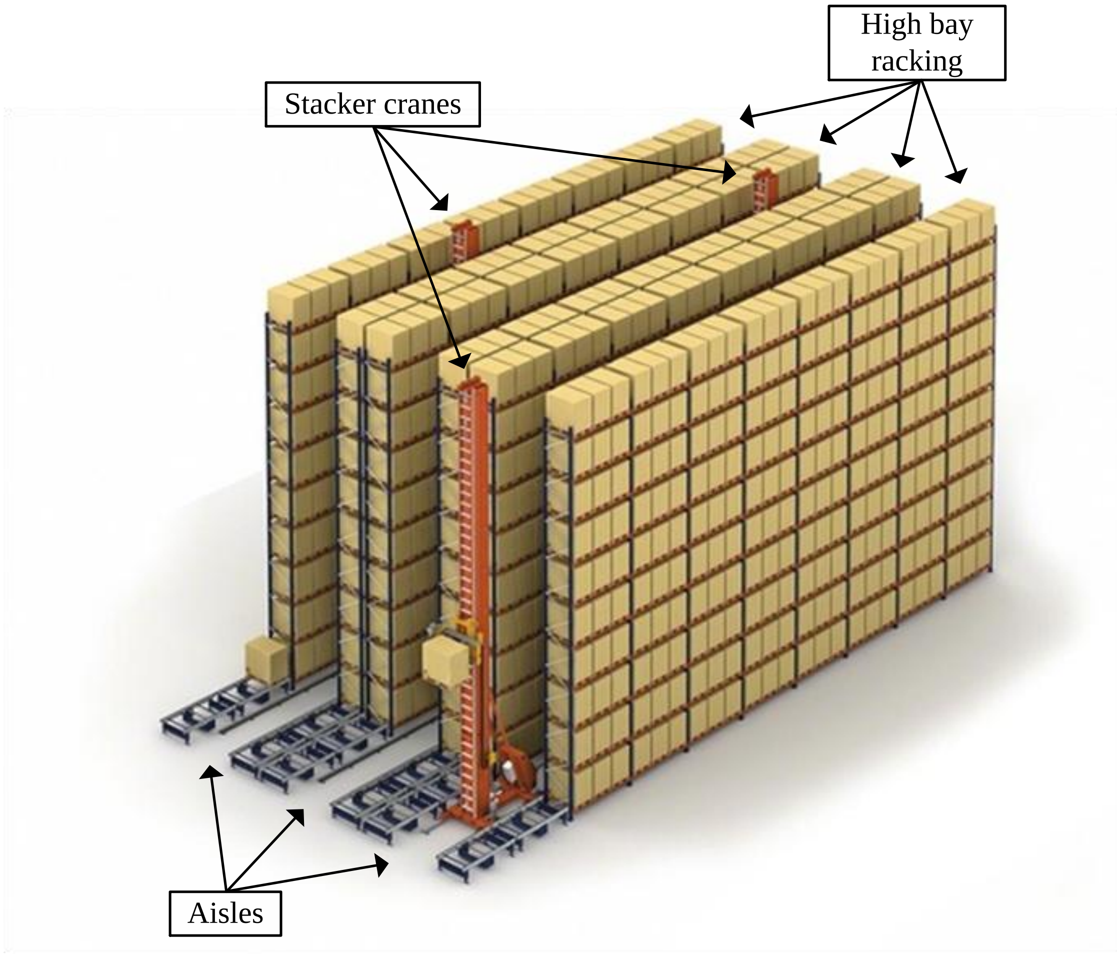

Figure 1.1 *Visualization of an example AS/RS* [3].

AS/RS can be a complex system [4]. Practical reasons for this are, for example, warehouse size, aisle amount, several stacker cranes moving on same aisle, or high receiving and picking amount requirements. A complex system requires a lot of designing, accomplishing the designed solutions, and testing to find and fulfill the customer requirements and expectations. [5] The long lasting development project and even utilization of an AS/RS could be simplified and improved if there were simulation model to present and test the features of the system. In this thesis, an example of simulation utilization during an AS/RS development project will be introduced.

In this section, motivation for the simulation utilization during an AS/RS development project and state of the research in the field will be presented. The research questions and goals, and utilized methodology will also be introduced. Lastly the structure of the thesis is described. The main goal of this section is to make the reader aware of the research challenge, which this work is going to focus on.

1.1 Motivation

The motivation for this work is finding a solution that enables validation of the AS/RS layout and functionality during the design phase. This validation is important for all stakeholders of the development project. Possible stakeholders are customer and designers of the AS/RS. Value for the customer would be that they could make the investment decision after they are sure that the designed system really fills their requirements. The benefit for designers is that they get confirmation if the system works as expected. Possible modifications are easier to perform during the design phase compared to the commissioning phase.

Warehouse operations include uncertainty [6; 7]. Uncertainty occurs in operational, tactical, and strategic levels. The uncertainties must be taken into account in the design. During an AS/RS design, possible uncertainties are included in technical parameters of the system or in AS/RS operational principles. If designed system is sensitive for variation in uncertain parameters, then, design modifications might be required. Furthermore, stakeholders need reliable system that is functional even if uncertainty presents. Another motivation for this work is finding solution for assessing sensitivity of designed AS/RS.

In the following subsections, the field of AS/RSs will be discussed in more details. Firstly, design procedure of an AS/RS will be presented. Secondly, the strengths and weaknesses will be introduced to clarify the reason to utilize AS/RSs. Thirdly, the complex nature of AS/RSs is presented.

1.1.1 AS/RS design procedure

AS/RS design phase from the first layout drafts to the fully functional warehouse can take even years. Therefore, need for the continuous system design validation is significant. The design phase can be separated to three levels: strategic, tactical, and operational level [8]. Gu et al. define five decisions to be made on strategic and tactical level [9]. The required decisions are presented in Table 1.1.

Table 1.1 *Decisions to be made during AS/RS development process on strategic and tactical levels.* [9]

Required decision in AS/RS development	**Explanation**
Overall structure	Define the order handling in the warehouse and the functional areas. The goal is to reach receiving and picking requirements.
Sizing and dimensioning	Determine the capacities of the functional areas.
Layout	Determine the actual physical lay of the functional areas.
Equipment selection	Decide the equipment utilized in the warehouse e.g. the stacker cranes.
Operation strategy	Determine the high-level utilization strategy of the warehouse.

On operational level the decisions are made to full fill the requirements set at the tactical and strategic levels. Operational level decisions are, for example, task creation for movable equipment and task scheduling. [5] p. 6

1.1.2 AS/RS strengths and weaknesses

An AS/RS has various benefits compared to non-automated warehouses. Example benefits are:

- Lower labor costs
- Lower floor space requirements
- Increased reliability and lower error rates
- Increased safety
- Product tracking and data collection are automated.

The reason for these advantages is automated functionalities of an AS/RS. For example, human mistakes and corrupted inventory are avoided because operators are not working in the warehouse. Stacker cranes also require less space to store the products and move between the racks compared to operator driven forklifts. The collected data can be analyzed, for example, to optimize the warehouse usage based on the seasonally varying supply and demand. [1]

On the other hand, one disadvantage of an AS/RS is high investment cost. Zollinger presents a price comparison of manual and automated warehouse in [10]. In the example, capital costs of AS/RS (8.0 M$) are 1.2 million dollars higher than costs of manual warehouse (6.8 M$). However, annual operation costs for AS/RS (216 k$) are lower than costs for manual warehouse (782 k$). If operation costs are mentioned, the automated warehouse will pay back the capital cost difference in 2.13 years.

Other disadvantages of AS/RSs are lower flexibility and required investment in the control system [1]. AS/RS is designed to fill specific requirements that can be, for example, receiving and picking amount requirements. If supply and demand of the stored products varies, then, also storing principles may need modifications. Therefore, requirements for the AS/RS and operational principles have to be concentrated precisely.

1.1.3 AS/RS complexity

In general, the complexity of warehouses is increasing. Especially in North America and Western Europe, the automation level of warehouses is increasing and construction of AS/RSs is a sign of this. [5, pp. 5] Reasons for this are a need to decrease the operational costs of the warehouses and difficulty to find qualified staff [11; 12].

Warehouse complexity is increasing because amount of different products to be stored is also increasing [13]. There can be tens of thousands different products stored in a single warehouse. Furthermore, there can be thousands of product suppliers and the products must be delivered to several consumers. The consumers can be other warehouses, stores and also internet customers. All of the consumers have their special requirements for the shipments. Other warehouses possibly require bigger deliveries. Stores require compact deliveries where products are ordered so that they can be placed straight in the shelves without extra ordering. Internet customers make usually small orders. General trend in warehousing is increasing order frequencies and decreasing order sizes. Warehouses are coming more responsive since the consumers expect shorter delivery times. [5, pp. 4 – 5]

Complexity of a warehouse increases also if racks have so called deep channels [1; 14]. The simplest racking type is single deep rack where only one product or pallet is stored depth wise. Then, stacker crane has straight access to all of the stored products. More complex racking types are double and multi deep racks. In double deep rack there are two and in multi deep rack there can be several products or pallets depth wise. The situation gets even more complicated if double or multi deep channel has various products stored [15]. These channels are called as mixed double or mixed multi deep channels.

The AS/RSs are complex units and designed case by case. One solution will not fill the requirements of all projects and design phase should be started again from the very beginning [5]. In the beginning of a project, it is impossible to accurately determine, how everything is finally going to work in the utilization phase. Therefore, it would be valuable to somehow visualize and test the designed AS/RS functionality during the design phase.

1.2 State of the art

On the area of automated storage and retrieval systems, academic research has been accomplished widely. It is possible to identify at least four reasons for this trend. Firstly, AS/RSs were introduced already in the 1950s, and therefore, there has been time for the research. Secondly, AS/RSs are commonly used, so, there has been motivation for the research. [1] Thirdly, various research questions have been available because of the complex nature of AS/RSs [5]. Fourthly, warehousing contributes to significant part of the logistics costs of companies. Reference [16] presents that about 20 % of the logistics costs are caused by warehousing.

Roodbergen et al. give an overview of some design and control issues in AS/RSs [1]. The issues are related to *system configuration*, *storage assignment*, *order batching*, *dwell point location*, and *performance measuring and analysis*. *System configuration* means generally the issues in AS/RS design phase. An AS/RS has to fill capacity requirements without causing bottlenecks and overcapacity. AS/RS is not really flexible in terms of operational principle changes, so the system is required to be designed right at once. *Storage assignment* is related to receiving and picking the products into and out from warehouse. There are several methods available for taking care of the storage assignment. *Order batching* concerns the picking procedure. Orders can be picked one by one, but usually it is more efficient to pick several orders at a time. Picking several orders at a time is called as batching. However, if batching is performed, then, the principles for it have to be decided. *Dwell point location* means that where an idle stacker crane should be located. After a stacker crane is ready with the last task, control logic need to make decision that where the machine is sent to wait for the next task. *Performance measuring and analysis* mean evaluation of the system functionality. In different cases, different features of the system are critical. Therefore, the system performance should be assessed case by case. Reference [1] gives an overview of these issues related to AS/RSs with example studies from literature.

To cope with various issues in AS/RS design and control, simulation has played a key role in the research. Gagliardi et al. give a literature review of modeling and simulation of AS/RSs in [17]. They focus both on dynamic simulation based models and static approaches based on travel-time modeling. Authors state that dynamic simulation models are able to integrate dynamic nature and stochasticity of systems to models. However, the weakness of both simulation and analytical modeling is that they are in-flexible and case-specific. Modeling studies are also usually performed for small and simple AS/RSs, and models are not easily or at all scalable to bigger real-life systems.

Examples of simulation studies of AS/RS are in [18-21]. In the simulation studies, example goals are equipment utilization ratio analysis, idle time minimization, and bottleneck detection. With simulation it is possible to analyze and improve the AS/RS performance if weaknesses mentioned in [17] (e.g. in-flexibility and case-specificity) are accepted.

Beside the AS/RS simulation studies, optimization research has been performed widely. References [16; 22] give an overview to general warehouse optimization and also AS/RS optimization is discussed. Because AS/RSs are fully automated, fruitful topics for optimization research are available. References [23-29] focus on optimal routing of the resources of warehouse. Scope of the research is finding the optimal route for the resources that minimizes travel time in the warehouse. It is possible to optimize the routes but also the order of product picking and placing affects the total travel time [30]. Also finding an optimal rack structure for AS/RS has been researched in [31-33].

In Subsection 1.1 requirement for uncertainty significance assessment was discussed. In literature, common method for assessing uncertainty significance is sensitivity analysis. Sensitivity analysis means variation of uncertain input parameters and analyzing the output behavior. With sensitivity analysis, the most significant uncertain parameters can be detected. Examples of sensitivity analysis utilization in warehouse environment are in [6; 7]. Other examples of sensitivity analysis use in simulation studies are in [34; 35]. Sensitivity analysis gives an overview of system functionality if input variables are uncertain. Also, significance of the uncertain parameters can be assessed. The weakness of sensitivity analysis is mentioned to be that several simulation runs are required to get comprehensive results and it can be time consuming.

1.3 Research questions and goals

The goal of this work is to test and evaluate functionalities of an example AS/RS during the design phase with simulation. The goal is divided into three research questions below. All of the questions are qualitative issues dealing with applying the simulation to AS/RS development project.

RQ1. What are the requirements for simulation platform to simulate an AS/RS?

RQ2. How performance measurements of an AS/RS vary when production and order amounts are varied?

RQ3. What is the sensitivity of an AS/RS with respect to the variables causing uncertainty in the system? How the sensitivity could be analyzed with simulation?

To answer the first research question, various requirements for the simulation platform will be listed. The requirements will base on simulation of the example AS/RS. The requirements will be separated to categories that are *general requirements, modeling the devices, production and order generation, warehouse management system, and performance measurements.*

To answer the second research question, two performance measurements for AS/RS assessment will be introduced. Measurements are device utilization ratio and realized picking and receiving amounts. These performance values will be measured from the example AS/RS when the designed production and order amounts are varied. Result will be visualization and assessment of the performance values.

To answer the third research question, three uncertain parameters of the example AS/RS have been chosen. The uncertain parameters are movement times of industrial robots, total delay of stacker crane work cycle, and warehouse utilization. Sensitivity analysis for the simulation model will be performed based on these uncertain parameters. In sensitivity analysis, the uncertain parameters will be varied and effects on output variables will be analyzed. The output variables will be utilization ratios of stacker cranes and industrial robots, and realized picking and receiving amounts.

1.4 Methodology

In this work, two main methods will be utilized. They are simulation and sensitivity analysis. Simulation means imitation of a process or system over time. Simulation study begins with problem formulation and model definition. Also goal of the study must be discussed to reach satisfying results. Then, actual simulation model is constructed and test runs are performed. After the model is validated, simulation runs will be designed and executed. Finally, simulation results are analyzed and reported. [36; 37]

The reason to utilize simulation is result of the complex and uncertain nature of AS/RSs. The strength of simulation is that it gives an overview of the AS/RS functionality and stochasticity is possible to be included in simulation model. Depending on the utilized simulation tool, it can take only a few hours to construct quite comprehensive simulation model. However, decision between simplifications and detailing must be considered because results of too simplified model can be useless. On the other hand, construction of too detailed model can be time consuming and expensive. If results of simpler model would be satisfying enough, then, modeling of extra details is waste of time and money.

Based on literature, simulation has given promising results in the field of AS/RSs. Examples are in literature reviews [1; 17] and in their references. The weakness of simulation research examples is that models are usually constructed of small and simple AS/SRs. However, references and their results motivate to utilize simulation in this work.

Another method utilized in this work is sensitivity analysis. Sensitivity analysis will be utilized for testing significance of uncertain parameters of the example AS/RS. In sensitivity analysis, for example, uncertain input parameters are varied, and then, the effect on output variables is analyzed. If variation of uncertain input parameters causes significant and intolerable changes in output variables, then, changes in the design are required. [34]

Warehouses are uncertain environments [6; 7]. This work will focus on uncertainty in technical parameters and utilization ratio of the example AS/RS. At worst, uncertain input parameters can affect the AS/RS functionality so much that AS/RS does not fill the set requirements. This should be identified with sensitivity analysis during the design phase before actual AS/RS construction begins.

Results of sensitivity analysis in literature motivate to use it. Example results are in [6; 7; 34; 35]. Sensitivity analysis is used for three different scenarios. Firstly, it is used to assess significance of uncertain parameters. Secondly, effect of general parameter variation is assessed. This can give important information of system functionality for designers. Thirdly, model robustness can be assessed with sensitivity analysis. If model is not robust for changes in input parameters, then, need for design modifications should be considered. [34]

1.5 Structure of this thesis

This work is separated into seven sections. Section 2 presents the methodology utilized in this work in more details. In Section 3, the simulated AS/RS will be introduced as experimental setup. The introduction is divided into general design, mechanical and automation design, and warehouse management system. Also modeling of the system will be discussed. Section 4 presents the actual experiment. The experiment consists of material flow simulations and sensitivity analysis simulations. The results of the simulations are presented in Section 5. Based on the results, the research questions will be answered in Section 6 in the discussion part. Section 7 concludes the work and provides topics for the future research.

2. METHODOLOGY

This section presents the methodology utilized in this work in. Subsection 2.1 focuses on simulation introduction. Also discrete-event simulation, pros and cons of simulation, utilized performance measurements, and steps of a simulation study will be presented. Uncertainty will be introduced in Subsection 2.2. In Subsection 2.3, sensitivity analysis will be presented.

2.1 Simulation

In [36, pp. 1], Law et al. introduce simulation as techniques that are used to imitate the operations of various different real-world facilities or processes. The definition for simulation by Banks et al. in [37, pp. 3] is almost equal. Only difference is that they mention that simulation is produced over time.

The simulated facility or process is often called as system. If you would like to analyze the system scientifically, you have to make a bunch of assumptions about the system functionalities. These assumptions are formed as mathematical or logical relationships and those together build up a model. The model is utilized to gain information and understanding of operation of the modeled system. [36; 37] Simulation can be utilized to estimate and evaluate the functionality of the simulated system. With simulation you can find answer to various “what-if” -questions. These questions may appear in case of developing something new or updating functionalities of something existing. New features may be tested and validated with simulation before actual construction or update project physically begins. [37]

If a system is simple enough, it can be modeled with mathematical methods (such as differential calculus, probability theory, algebraic methods). The solutions of the models are usually numerical values that are measures of performance of the system. This is called as an analytical solution. However, real-world systems are usually too complex to be modeled analytically. Still, these complex systems can be imitated with simulation. Simulation provides data of the system as it was a real system. This simulation data can be utilized to evaluate the performance of the system. [36; 37]

There are various real-world systems to be simulated. Therefore, there are different simulation models available and they can be separated along four different dimensions:

- **Static vs. Dynamic Simulation Models**: A static simulation model is presenting a system at exact point of time or time does not have effect on the system. More often simulations are dynamic where the system evolves over time. An example of dynamic simulation is simulation of stacker crane moving in an AS/RS.

- **Deterministic vs. Stochastic Simulation Models**: The property of deterministic simulation model is that it is not affected by any probabilistic (random) components. Deterministic simulation models are represented by physical laws that are described by differential equations. Simulation of chemical reaction could be example of this kind of model. As a comparison, the output generated by stochastic model is random in itself. This is the reason why the output of stochastic model should be treated only as an estimate of the real output.
- **Continuous vs. Discrete Simulation Models**: For continuous simulation models the state variables change continuously with respect to time. For example, simulation of car movement is continuous model because the velocity and position are changing continuously with respect to time. For discrete simulation model the state variables are changing only at separated points in time. A warehouse is an example of discrete system. The number of products in the warehouse varies only when movable equipment brings products from production to the warehouse or picks orders from the warehouse. It is important to notice that continuous model is not always used to model continuous system and vice versa. The choice between discrete and continuous model depends on the specific objectives of the simulation study. [36, pp. 4 – 7]
- **Integer vs. Real State Variables**: The models can also be separated according to the data type of state variables. Data type of state variables can be either integer or real. Amount of products in a warehouse is an example of state variable that is integer valued. Speed of a stacker crane is example of state variable that is real valued. However, a complex simulation model may also include both integer and real valued state variables. [37]

In this work, the presented simulation model will be discrete, dynamic, and stochastic. This kind of model is called as a discrete-event simulation (DES) model. In the example model, there will be both integer and real valued state variables.

2.1.1 Discrete-event simulation

To understand the meaning of discrete-event simulation, some terms must be defined. Objects and components of the simulated system are called as *entities* and entities have properties, *attributes.* An *activity* is representing a time period of specified length. Bank is a simple example of a system. In a bank, customers are example entities and balance in their checking accounts is an attribute. Making deposits might be an activity in a bank. It is important to notice that all of the possible entities, attributes and activities are not required to define a system for simulation study. Only relevant features should be taken into account. [37, pp. 8, 61]

A system has a *state*. The state is a collection of *state variables*. Those describe the system at a particular point of time. In the bank example, possible state variables are number of busy tellers, the number of customers being served, and arrival time of the next customer. An *event* can change the state of a system. In a bank, example events are arrival of a customer and completion of customer service. [37, pp. 9, 61]

In discrete-event simulation the state of the simulated system changes only at separate points in time. It can be also said that the amount of state changes is not infinite. One strength of discrete-event simulation is that time between the events is not meaningful because then the state does not change. Therefore, time between events can be skipped and it makes the simulation faster. [36, pp. 7] Skipping time periods during the simulation creates a need for mechanism that keeps track of the simulation time.

Generally utilized mechanism to keep track of the simulation time when simulation proceeds is *next-event time advance*. General flow for the discrete-event simulation using next-event time-advance approach is in Figure 2.1.

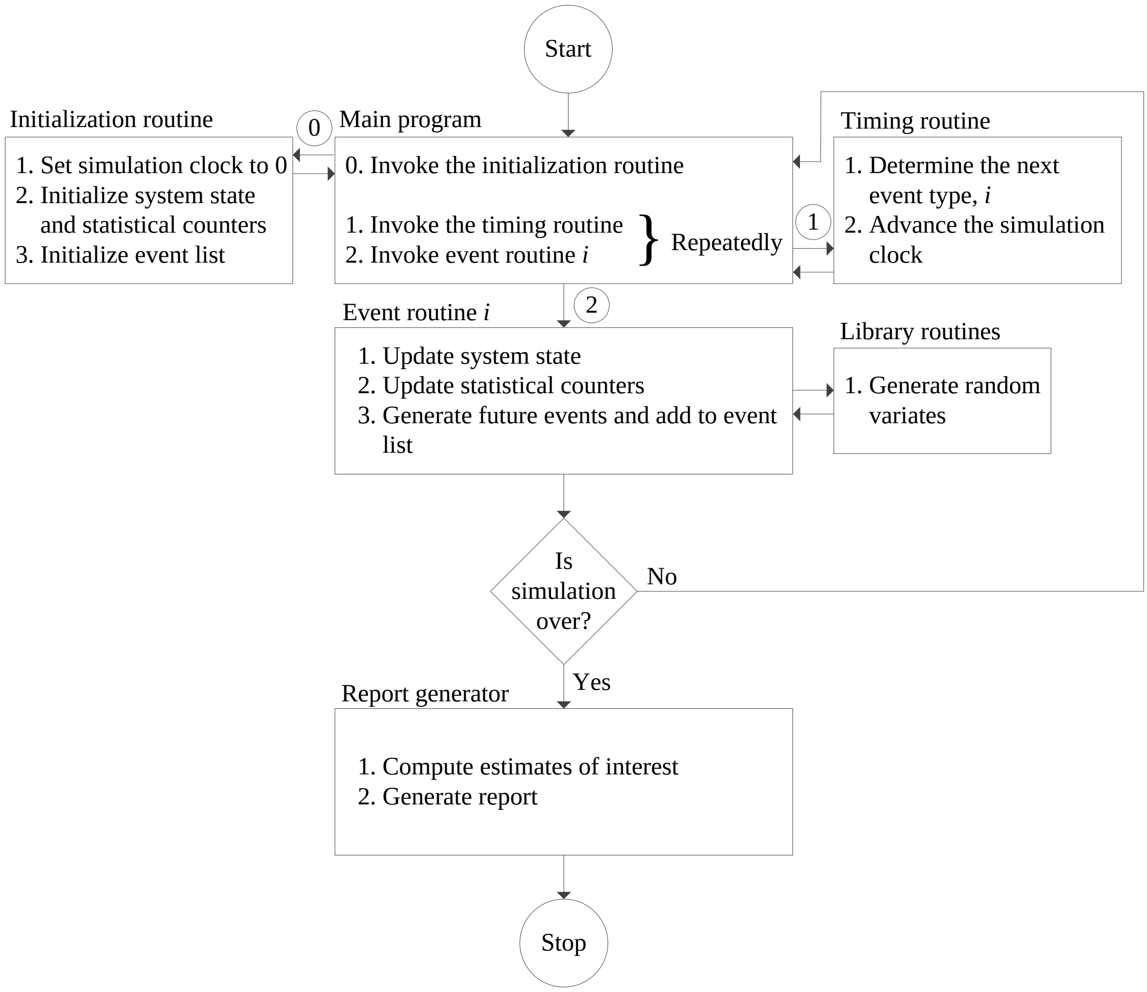

Figure 2.1 *General flow of discrete-event simulation using next-event time advance. Figure is adapted from* [36].

If next-event time advance is utilized, the simulation clock is initialized to zero and times for future events are determined by initialization routine. Then, when the simulation starts, the simulation time is advanced to the time when the first event occurs by timing routine. At that time the event is performed and system state changes by event routine. Also the list of future events is updated and the currently performed event is removed from the list. Then, if simulation is not over, the simulation clock is advanced to the time of the next event, and the system state and future event list are updated, etc. Then, this procedure is continued until some predefined stopping condition (e.g. point of time or number of occurred events) is satisfied. After the simulation is finished, typically a report is generated about the simulation results. [36, pp. 8 – 13]

2.1.2 Advantages and disadvantages of simulation

As mentioned in the introduction of this thesis, simulation is widely used in the field of warehouses and AS/RSs. This is a result of the advantages of the simulation. In Table 2.1 is a list of some of them presented by [36-38].

Table 2.1 *Some advantages of simulation.*

	Advantage of simulation
1.	Testing new functionalities of an existing system is possible without disturbing the ongoing operation of the system.
2.	Designed system (physical layout, capacity of connected equipment, transportation system, etc.) can be tested before resources are used for the physical implementation. Simulation can also assert the customer about the functionality of the design before the system purchase.
3.	Comparison of different solutions is possible.
4.	Time can be compressed and expanded in simulation so speed-up and slow-down of the simulation is possible.
5.	Bottleneck identification also in complex system is possible. Bottleneck can be spotted as extra delays for information, materials, etc.
6.	Simulation shows how system operates instead of how individuals think the system operates.

There are lots of advantages in the simulation, but also drawbacks exist. Some of the drawbacks are presented by [36-38] and those are presented in Table 2.2.

Table 2.2 *Some disadvantages of simulation.*

	Disadvantage of simulation
1.	Learning the model building requires training and experience. Different simulation tools offer their own easy-to-use user interfaces but still modeling the complex systems requires experience.
2.	Model building requires time and effort. Especially, if the problem formulation and goals are defined inadequately or there are not enough resources, the results may be dissatisfying.
3.	Simulation can be used even if analytical solution is easily possible. Analytical solution should be preferred if finding it is not too complicated.
4.	To reach reliable simulation results, several simulation runs are required. Results of a stochastic simulation run are only estimates. Therefore, the significance of the randomness should be identified with several simulation runs.

The significance of the disadvantages of the simulation should be evaluated case-by-case. If need for the simulation is infrequent, utilization of simulation consultant can be profitable. This could help to avoid the first two disadvantages. Also meaning of the fourth disadvantage should not be overwhelming because computing ability of the computers increases all the time. After all, simulation is an efficient tool if the problem formulation and simulation study planning have been performed well. These are the beginning for a simulation study.

2.1.3 Goals and performance measures

Especially in material handling system (e.g. AS/RS) simulations, the goal of the simulation studies is insight, not only numbers. The stakeholders of the simulation study want to gain insight of how the new or modified system will work. After the general material flow and system functionality is understood, numerical performance values step forward. [37, pp. 425 – 435] In this work, the focused performance measures will be AS/RS receiving and picking amounts and device utilization ratios.

Key features for AS/RS are receiving and delivering products to and from the warehouse. Receiving means taking care of the products that are coming into the warehouse. Products may come from production or from other warehouses. In this work, product is counted as received when it arrives to the system. Delivering means picking ordered products from the warehouse. In this work, product is counted as delivered, when it leaves the system. Average amount of received or delivered products in a time frame is used as a performance measure for the warehouse. The time frame is typically minute, hour, or day. [16]

Device utilization ratio ρ means percentage of time a device is busy. Approximation of it ($\hat{\rho}$) can be calculated with Equation 2.1.

$$\hat{\rho} = \frac{T_b}{T_S} * 100\%. \qquad 2.1$$

In the Equation 2.1, T_b is the time when a device is busy and T_S is the simulated time. Approximation of device utilization ratio gets closer to the actual ratio (ρ) when $T_S \rightarrow \infty$. If device is not busy, it can be, for example, idling or blocked. Idling means that device is waiting for products coming from previous devices. Being blocked means that the device cannot deliver products further because following devices are busy. By comparing busy, idle, and blocked times, it is possible to spot so called bottlenecks in the system where extra capacity is required. [37, pp. 189 – 193, 425 – 435]

2.1.4 Steps of a simulation study

Simulation study can be distributed in 10 different steps [36, pp. 106 – 109]. Figure 2.2 presents the steps in order.

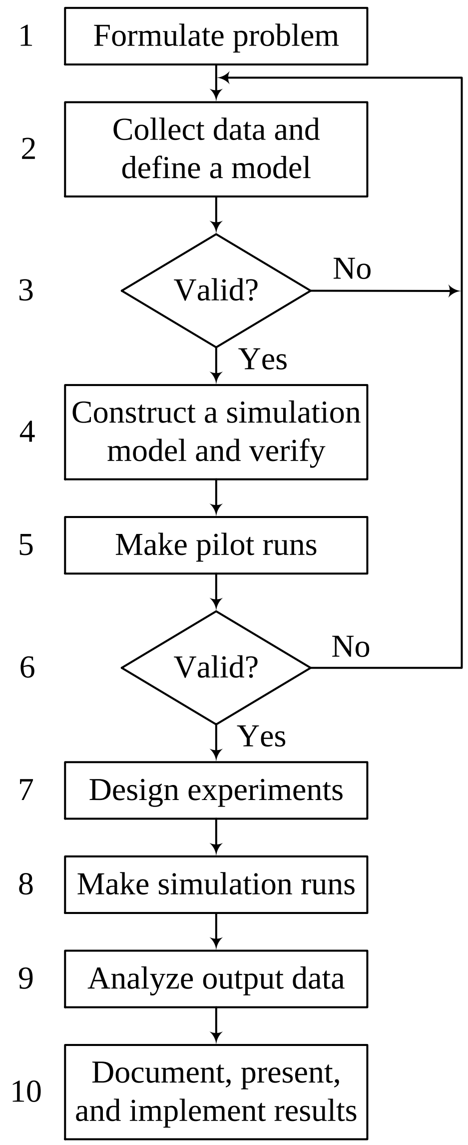

Figure 2.2 *Simulation study distributed in 10 steps. Figure is adapted from* [36].

As Figure 2.2 presents, simulation study is an iterative process. The first two steps define the simulated problem and ways to solve the problem. After that, the first validation is done. However, according to the presented workflow, step 1 is never returned. This emphasizes the importance of problem formulation and planning of the study. If these are generated properly, it also saves time because goal of the study is not changed during the process.

After steps 4 and 5, the simulation model is generated and test runs are ready. The following step is validation which is again important, because actual production runs should not be made with dissatisfying model. After the model is ready, the experiments should be designed, implemented, analyzed, and reported. In real life, there may be iteration also between these phases. Experiments mean different simulation scenarios which test the model functionality in various situations. Between the scenarios, for example, input data (input volume, input product distribution, etc.) or uncertain model parameters (equipment properties, capacities, etc.) may vary.

In Figure 2.2, the presented simulation study procedure is a generalized structure. Every simulation study is individual and it is possible that study includes less or more steps. Law et al. also mention in [36] that during a simulation study, more knowledge of the system is probably gained. Therefore, changing the scope of the study may become necessary. [36]

In this work, uncertainty and sensitivity analysis are utilized as part of steps 7 – 9. Those will be presented in the following subsections.

2.2 Uncertainty

Model is always an imperfect imitation of a real-world system. As mentioned in Subsection 2.1, a bunch of assumptions have to be made when system is modeled. Even if assumptions may be known to be close to the truth, still they are inaccurate. Uncertainty in the system may be related to input data, parameters, and properties of the model. The result of this uncertainty is imprecision and uncertainty in the model output. [39, pp. 255]

In this work, uncertainty is defined as what is not certain is uncertain [39]. In an automated storage and retrieval system, an example uncertainty is warehouse utilization principles. This means variation in product types and amounts that are stored to and picked from a warehouse. Principles also affect the warehouse capacity that is in use. Based on the customer data and expectations, different warehouse utilization scenarios should be identified. If some principles can not be accurately identified from data or expectations, then, uncertain assumptions are required.

Some uncertainty in the modeling may be reduced by further research, data collection and analysis of the modeled system. Before beginning the further operations, it is reasonable to estimate, what will be the gained value of removing the uncertainty compared to the price of required operations. If the uncertainty is only remotely or not at all significant, then, the uncertainty can be accepted. [39, pp. 255]

On the other hand, if uncertainty reduction is found to be worthwhile, then, it should be considered. In uncertainty reduction, it is important to focus on reducing the significant uncertainty instead of insignificant. Identifying the difference between significant and insignificant uncertainty is result of uncertainty assessment. It should be performed in co-operation with stakeholders of the simulation study. [39, pp. 255]

Avoidance of the uncertainty identification and reduction can make the model useless. At worst, further decisions may base on useless model results. Then, also the decisions are poor. Therefore, high quality model without significant uncertainties should be a basis for the further decisions made. [39, pp. 255]

Modeling an existing system includes less uncertainty. From an existing system the input data is possible to collect, parameters for the model can be identified, and output data can be compared to the output of the model. This information is not partly or at all available for a system that is in the development phase. Then, assumptions are required and model includes more uncertainty. In case of modeling an existing system, expected future changes make the modeling more uncertain. Historical data and current conditions of the system do not describe the future if modifications are expected. Therefore, uncertainty causing assumptions are required. [39]

2.3 Sensitivity analysis

Sensitivity analysis explores and quantifies the influence of possible errors and uncertainties in the model inputs to the model outputs. [39, pp. 256] The concept of sensitivity analysis is presented in Figure 2.3.

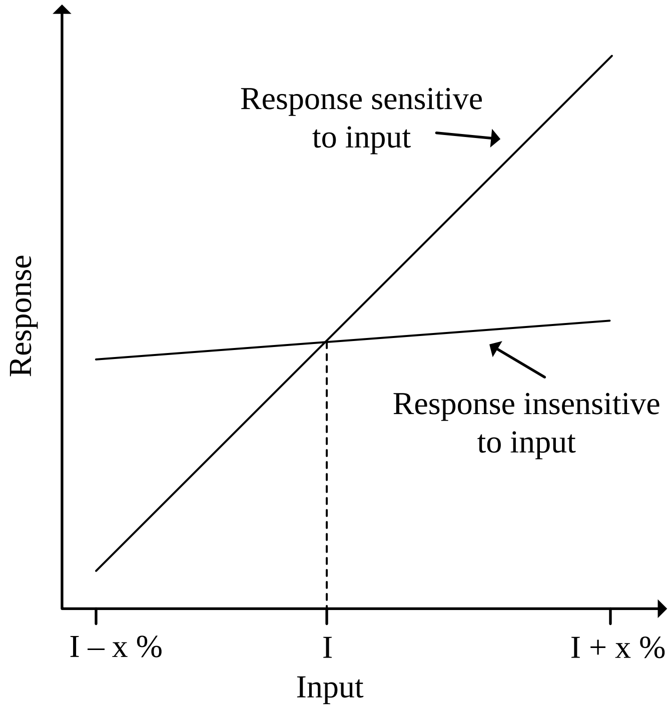

Figure 2.3 *The concept of sensitivity analysis. Figure is adapted from* [34].

In sensitivity analysis, input (*I*) is varied between *I – x %* and *I + x %* as Figure 2.3 presents. Value of *x* is based on analysis of input (*I*). The sensitiveness of response variable related to input is then measured. If the shift in response is significant, then, response is sensitive to input. On the other hand, if the shift in response is insignificant, then, the response is not sensitive to the input. Shift significance can be analyzed from the gradient steepness. [34]

The strengths of sensitivity analysis appear in three sectors:

1. Assessing uncertainty significance
2. Effect of model parameter variation
3. Model robustness assessment

All of the sectors provide important information for the stakeholders of the simulation project. With sensitivity analysis, parameters causing the most significant uncertainty can be identified. Then, the uncertainty can be reduced with further system research and assessment. The second sector, parameter variation effects, can help the designer to choose devices that provide enough capacity but not too much. Choosing a device with lower capacity can save money but still the device may fill requirements. Model robustness assessing is also important for the stakeholders. If small changes in model parameters make the simulation results unsatisfying, it can push the stakeholders towards more robust design. [34] In this work, the scope of the sensitivity analysis will be on uncertainty significance assessing.

3. EXPERIMENTAL SETUP

As experimental setup for this work, an example automated storage and retrieval system will be introduced. The AS/RS is under development during the thesis writing. Therefore, there is practical need for the results of this work. In Subsection 3.1, general design of the AS/RS is introduced. More detailed level design will be presented in Subsections 3.2 and 3.3. These subsections will focus on mechanical, automation, and warehouse management system design. In Subsection 3.4, modeling of the AS/RS will be discussed.

3.1 General design of an example AS/RS

The example AS/RS consists of aisles, stacker cranes, high bay racking, industrial robots, packing stations and conveyor system. In this work, simulation and validation of the product flow is the key issue. Mechanical trajectories and physical capabilities of the equipment are not concentrated. Therefore, there is no need for the information about the stored products. In the rest of the work, the stored products are called generally as products.

The high bay racking consists of 44 160 storing channels. The average maximum filling capacity of the warehouse is 529 920 products. The average and maximum receiving and delivering capacities of the AS/RS are presented in Table 3.1.

***Table 3.1** Receiving and picking capacities of the AS/RS.*

Measure	Avg.	Max
Products from production to storage	625 products/h (15 000 products/24 h)	2292 products/h (55 000 products/24 h)
Products from storage to picking	1250 products/h (30 000 products/24 h)	3334 products/h (80 000 products/24 h)

The promised receiving and picking capacities are calculated with storage utilization of 50 %. Storage utilization means occupied space as a percent of storage capacity [40].

To understand the functionality of the AS/RS, the basic input and output flows are introduced. Input flow or infeed means products that arrive from the production to be stored in the warehouse. The infeed procedure of the AS/RS is presented in Table 3.2.

Table 3.2 *The infeed procedure of the example AS/RS.*

	Step of the infeed procedure
1.	An automated guided vehicle (AGV) brings products from the production for warehousing.
2.	Products are moved automatically from AGV to a vertical conveyor. Vertical conveyor elevates the products to the level of conveyor.
3.	Conveyor system moves the products next to one of the industrial robots. The choice between the robots will be discussed in Subsection 3.3.
4.	Industrial robot picks products from the conveyor and places them to waiting area.
5.	A stacker crane is moving on an aisle. When picking task for the stacker crane is allocated, it moves next to the waiting area. Then, stacker crane picks the products.
6.	When stacker crane is loaded it moves along aisle to decided position. Then, the load of the stacker crane is unloaded to channel in a rack.
7.	Stacker crane is ready for a new task.

To understand the AS/RS functionality further, it is important to know that there are three conveyors next to the industrial robots. The conveyors are on top of each other. The uppermost conveyor takes care of the infeed of products. This is the reason why the vertical conveyors are elevating products to the level of the uppermost conveyor.

Two conveyors at lower levels are taking care of the output flow. The output flow or outfeed means products that are ordered from the warehouse. The upper outfeed conveyor reaches other half of the packing stations and the lower conveyor reaches the other half. General outfeed flow of the AS/RS is presented in Table 3.3.

Table 3.3 The outfeed procedure of the example AS/RS.

	Step of the outfeed procedure
1.	Warehouse management system decides which products are delivered based on the orders from the warehouse. This will be discussed later in Subsection 3.3.
2.	Warehouse management system allocates picking task for a stacker crane.
3.	Stacker crane moves along aisle to the position from where it can pick ordered products from a rack.
4.	Stacker crane moves and unloads the products to the waiting area. From waiting area the industrial robot picks products and places them on the other of two outfeed conveyors.
5.	Outfeed conveyor will move the products to one of the packing stations. Warehouse management system will make the decision about which packing station will be used.

In the following subsections the design of the AS/RS will be introduced in more details. All of the components that have been introduced in this subsection are going to be discussed.

3.2 Mechanical and automation design

Mechanical and automation design are the basis for a simulation work. The simulation in this work requires the information of the basic functionality of the devices. Also speeds, accelerations, and capacities are required.

AGV:

The link between production and AS/RS are AGVs. AGVs are the first components that will be modeled in the simulation even if those are delivered by another supplier. AGV modeling increases veracity of the simulation because also AGV properties can be validated.

AGV brings products from production as piles. Pile consists of 1 – 5 products that are on top of each other. The maximum height of a pile is 1 meter. AGV can carry 6 piles of products. Product piles are loaded on AGV on two conveyors three piles per side. Figure 3.1 presents the load on an AGV.

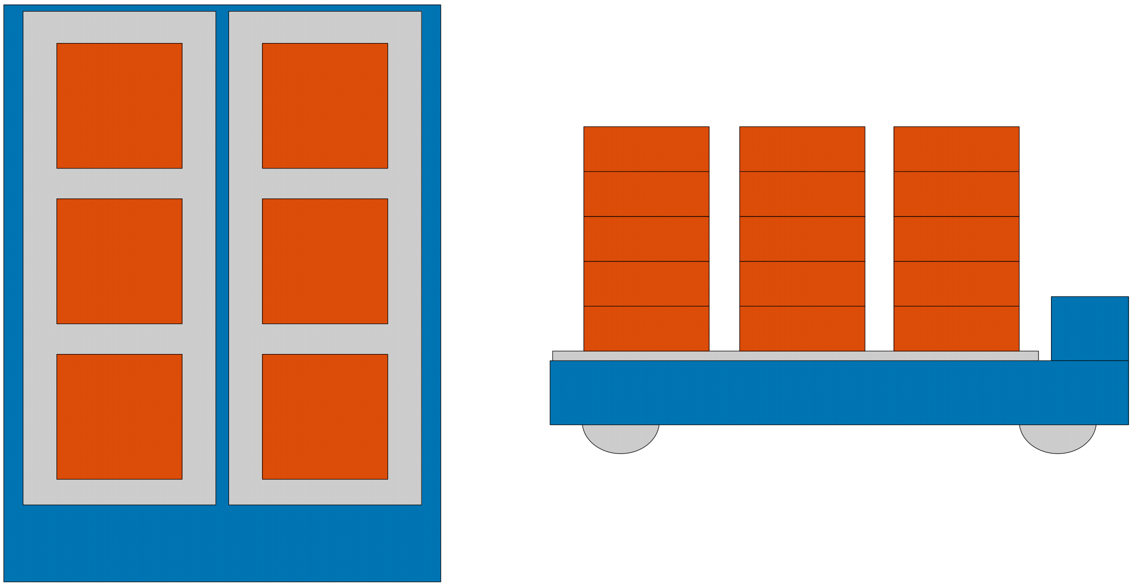

Figure 3.1 *AGV load from top and side views.*

The speed of the conveyors on AGVs is 0.4 m/s and acceleration is 0.5 m/s^2. When AGV arrives at vertical conveyor of AS/RS, it first unloads other side of the load. Then, AGV moves back and forth so that it can unload the other side of the load. The time that AGV requires to change the side is 15 seconds. After unloading the load, the AGV leaves and next AGV may arrive. The time for AGV change is 20 seconds.

Vertical conveyor:

The first components of the AS/RS are the vertical conveyors. The purpose of the vertical conveyors is elevating the products from the level of AGV to the level of the infeed conveyor. The elevated distance is 3 meters and elevation time is 4.9 seconds. The vertical conveyors have also horizontal conveyor for loading and unloading the equipment. The speed of the horizontal conveyor is 0.4 m/s and acceleration is 0.5 m/s^2.

The work cycle of a vertical conveyor begins with loading three piles from an AGV. When the vertical conveyor is loaded, it starts elevation. At the upper position, vertical conveyor is unloaded to the infeed conveyor. After the vertical conveyor is unloaded, it begins the depression. When the vertical conveyor is on the ground level, it is ready for a new load.

Conveyor system:

Conveyor system consists of both infeed and outfeed conveyors. The speed of the conveyors is 0.5 m/s and acceleration is 0.5 m/s^2. In the conveyor system there are several conveyors. The length of the conveyors varies between 1.5 meters and 11.5 meters. Conveyors are nonaccumulating.

There are different conveyors for different purposes: straight conveyors, curved conveyors, conveyor stops, and flow turning conveyors. The different conveyor types are visualized in Figure 3.2.

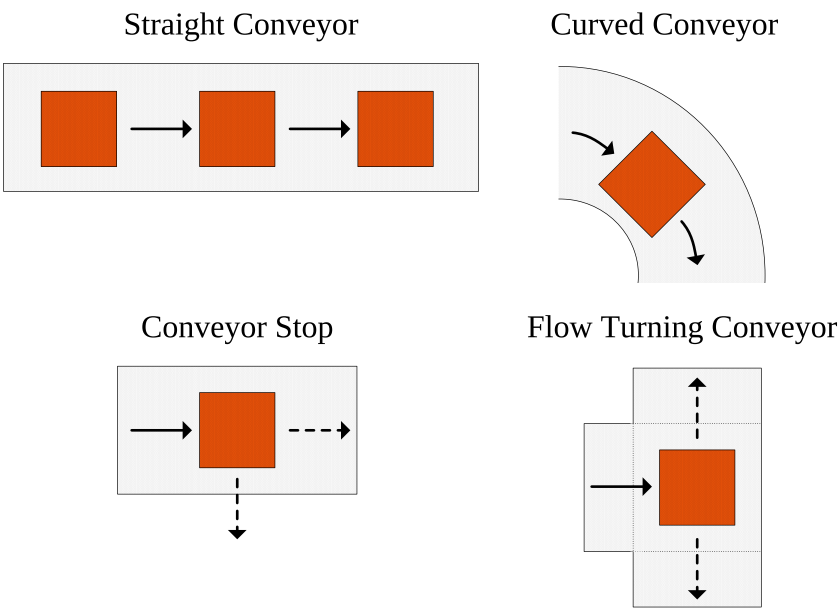

Figure 3.2 *Conveyor types in the system.*

Straight and curved conveyors are used to move the product flow from begin to end of a conveyor. Conveyor stops are short conveyors where industrial robots can pick and place product piles. Before pick or place move, the conveyor must be stopped and that is the reason to use conveyor stops. Flow turning conveyor is short conveyor that turns and distributes the flow.

Industrial robot:

Industrial robots are used to move product piles from infeed conveyor to waiting area and from waiting area to outfeed conveyors. The pile gripper picks the products pile by pile so the maximum load is 1 meter of products. Industrial robot picks infeed pile from a conveyor stop and places it on a holder for incoming products. For outgoing products there is own holder from where the industrial robot can pick a pile. Then, industrial robot places the pile to conveyor stop that is part of the outfeed conveyor line.

The working logic of the industrial robot is that it picks and places products always when those are available. If both infeed and outfeed are available, then, infeed is prioritized. The reason for this prioritization is that by picking first the incoming products, the possible blocking at the infeed conveyor is avoided or minimized. Blocking means that product pile going to further industrial robot is waiting behind the piles going to closer industrial robot.

Work cycle time of the industrial robot includes uncertainty because the development is still in progress. It is not certain that is it possible to use the maximum speed and acceleration of the industrial robots. A robot designer supplied an analysis about the possible movement times with maximum speed and acceleration. Moves are made between infeed conveyor stop, outfeed conveyor stops, infeed holder, and outfeed holder. The analysis results are presented in Table 3.4. Conveyor stop is abbreviated as CS in the table.

Table 3.4 *Movement times of industrial robots as seconds.*

Time (seconds)	Infeed CS	Outfeed CS (Higher)	Outfeed CS (Lower)	Infeed Holder	Outfeed Holder
Infeed CS	0.0	8.0	8.0	10.0	11.0
Outfeed CS (Higher)	8.0	0.0	8.0	10.0	11.0
Outfeed CS (Lower)	8.0	8.0	0.0	11.0	11.0
Infeed Holder	10.0	10.0	11.0	0.0	10.0
Outfeed Holder	11.0	11.0	11.0	10.0	0.0

The assumptions about the movement times will clarify during the development project. This uncertainty and analysis of its impacts will be discussed in more details in Section 4.

Waiting area:

Waiting area is the buffer area between industrial robots and stacker cranes. Industrial robots place the incoming products to waiting area and pick outgoing products from there. The stacker cranes are working the other way around, so, those place the outgoing products to waiting area and pick incoming products from there.

In the waiting area, there is own place for incoming products and own place for outgoing products. These are called as infeed holder and outfeed holder. Capacity of both holders is 6 meters. Therefore, the total capacity of waiting area is 12 meters of products.

Stacker crane and aisle:

Stacker cranes take care of storage and retrieval tasks in the example AS/RS. Visualization of a stacker crane with pallet fork and movement directions is in Figure 3.3.

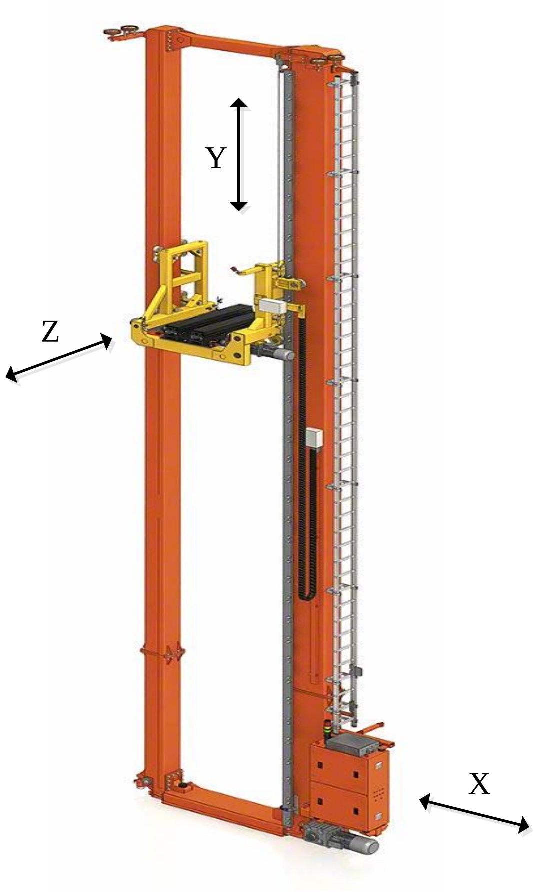

Figure 3.3 *Stacker crane with pallet fork and movement directions. Figure is adapted from* [3].

Stacker crane can move in three directions: X, Y, and Z. Movement to X direction means horizontal move along the aisle. Movement to Y direction is vertical movement of stacker crane. Movement to Z direction means moving into and out from the storing channels. Speed and acceleration parameters of the stacker cranes are presented in Table 3.5.

Table 3.5 *Speed and acceleration parameters of the stacker cranes.*

Direction	**Parameter**	**Value**
X	Drive speed	3.0 m/s
	Acceleration/deceleration	0.5 m/s^2
Y	Drive speed	0.85 m/s
	Acceleration/deceleration	0.5 m/s^2
Z	Drive speed loaded	0.7 m/s
	Drive speed unloaded	1.0 m/s
	Acceleration/deceleration	0.5 m/s^2

In the example AS/RS, stacker cranes have load handling devices with two forks. Capacity of a single fork is 3 meters so the whole capacity of a load handling device is 6 meters of products. Full stacker crane load consists of 6 piles, 1 meter each. The load is unloaded to two channels because channels are 3 meters deep each. One fork can pick and place varying amount of products with single move. The amount can be anything between one product and full load of a fork.

The stacker crane can be loaded from a storing channel or from infeed holder. The outfeed products can be picked from one or more channels (e.g. 1 pile from the first channel, 3 piles from the second channel, 2 piles from the third channel, and then, the load is full). The load of a stacker crane can be unloaded to a storing channel or to outfeed holder. Also unloaded products can be distributed to several storing channels.

The work cycle of a stacker crane is same at storing channels and waiting areas. The work cycle is presented in Table 3.6.

Table 3.6 *Work cycle of the stacker cranes.*

	Step of the work cycle
1.	Positioning (12 seconds)
2.	Move a fork in the channel
3.	Delay (2 seconds)
4.	Lift/depress the fork – pick/deposit products from/in the channel
5.	Delay (2 seconds)
6.	Pull the fork back from the channel
7.	Delay (2 seconds)
8.	Continue to the following task

Positioning means that after the stacker crane has driven close to the channel, it requires some extra time to find the accurate position. Positioning is done based on the sensor information. Therefore, the positioning time, 12 seconds, is just an approximation. Stacker crane also requires delays between the moves to make sure that the next move is safe. Also value for this delay is approximation by the designers. These uncertain delays and positioning times will be discussed in more details in Section 4.

Rack:

High bay racks are used for storing the products. The racking consists of 44 160 individual storing channels and all of them are 3 meters deep. All of the storing channels are equal.

Filling of a channel begins from the back of it. The first product is placed in the back and next product is placed in front of it, etc. The products that are behind others are blocked. Therefore, if the product that is stored first is wanted out from the channel, also the other products need to be picked out from the channel.

Packing station:

At packing station an operator takes products from a conveyor and moves them for further use. Packing station has an accumulating conveyor that can buffer products. Buffering capacity is 8 product piles per packing station. Operator's processing time is assumed to be 7.5 seconds per product. In this work the operator's detailed behavior is not relevant and therefore it will be simulated only as a constant processing time.

3.3 Warehouse management system

Warehouse management system (WMS) is the brain of an AS/RS. It provides information that is relevant in managing and controlling the product flow through the warehouse. WMS coordinates the products from production to storing channels and from storing channels to packing stations. [41]

Because AS/RS is only a part in the larger material flow, WMS must communicate with higher level systems. Communication includes information about the incoming products and future orders. In other words, communication includes supply and demand from the warehouse point of view. The higher level system is generally called as enterprise resource planning (ERP) system. WMS takes care of the product flow, so it has to communicate also with lower level systems. Systems, such as PLC, are taking care of the automation system and those send back data that is collected from the devices. [41] Figure 3.4 presents the connection of WMS to the other systems.

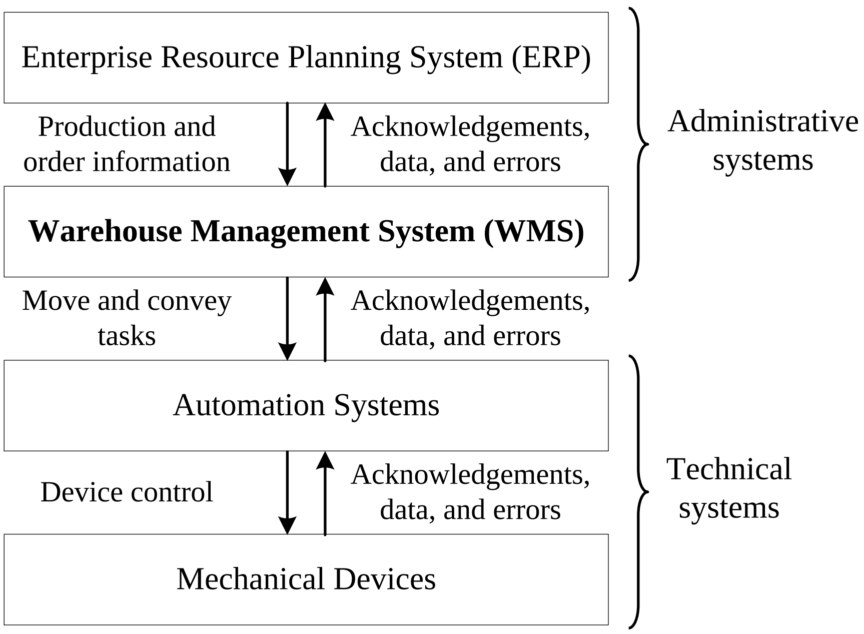

Figure 3.4 *WMS connection to the other level systems. Figure is adapted from* [41].

In the example AS/RS, there are 3 key assignments for the WMS. They are routing product piles in the conveyor system, storage strategy, and allocating picking and placing tasks.

Routing product piles in the conveyor system:

The automation system requires information about destination of the products. Destination is decided in both infeed and outfeed phases. In case of infeed, the decision about the destination is made after a product pile arrives by an AGV. WMS must make a decision that what industrial robot and stacker crane are used to store the arrived product pile.

There are two base rules for the product pile routing in case of infeed. Firstly, whole load of single AGV goes for same industrial robot and stacker crane. Secondly, AGV loads are distributed evenly to the industrial robots and stacker cranes.

In case of outfeed of the products, WMS must make decision that in what order the packing stations are utilized. This decision must be made when industrial robot places a product pile on an outfeed conveyor. There are two base rules for the outfeed. Firstly, products of whole order are delivered to a single packing station. Secondly, orders are distributed evenly to the packing stations.

Storage strategy:

Storage strategy means allocation of the storage channels for incoming products and choosing storage channels from where the products are delivered. From the warehouse performance point of view, the storage strategy is a key element. Therefore, it is important to use time and effort to find an effective storage strategy that meets the set receiving and picking amount requirements. [16] In this work the utilized storage strategy is random storage.

In case of random storage, the storing channel for every incoming product or pallet of products (in the example AS/RS, pile of products) is chosen randomly [16]. This means that all of the empty and suitable locations have equal probability to become as the chosen location [42]. The benefit of random storage is that the warehouse space utilization can be high because the locations are equally utilized. This may also result in low space requirements. The cost of the high space utilization is that the travel distances are increased. This is caused because fast moving products may be stored in the back of the storage and slow moving products can be stored in the front of the storage. [16]

When a product pile is coming in the warehouse, it requires an exact storing location where it will be stored. In the example AS/RS, WMS makes this decision when the loaded AGV has arrived to the system. Each of the product piles will get the storing location. Then, the automation system can derive, to which aisle the pile must be delivered. When the product pile has reached the correct aisle, stacker crane will carry the products to the correct storage location.

In the example AS/RS infeed storing, random storage strategy is manipulated so that whole load of an AGV will be assigned to the same aisle. Also if whole load of a fork on stacker crane fits in the randomly chosen storage channel, load will be placed there.

WMS makes also choice about picking the products. When ERP has ordered products from the warehouse, WMS makes randomly decision that from where the products will be delivered. Also in case of order picking, the random storage strategy is manipulated so that as many products as possible are delivered from a single channel. For example, if 15 pieces of products are ordered and there are two channels including 10 pieces of product each. Then, 10 pieces are delivered from the other channel and 5 from the other.

Allocating picking and placing tasks:

WMS must keep track of the future tasks for the stacker cranes. The tasks are generated based on the information about products coming from the production and orders that ERP sends. All of the tasks are prioritized so that the most important tasks are executed first. The prioritization is possible to be manipulated so that, for example, infeed tasks pass outfeed tasks in line. This prioritization may be required if infeed or outfeed is more critical.

In the example AS/RS, infeed and outfeed tasks are prioritized equally. This means that the task that has arrived first will be allocated first. The infeed task will be allocated for a stacker crane when an AGV has arrived to the system. The stacker crane will continue working with the older tasks and when those are ready, the stacker crane will execute the infeed task.

Outfeed tasks are generated based on the orders sent by ERP. It is possible that ERP sends the orders when those need to be delivered or in advance. In this work, outfeed tasks are generated immediately when orders are sent to the WMS.

3.4 Modeling

The example AS/RS is large and complex system with several stacker cranes, industrial robots, conveyors, AGV connections, and packing stations. Warehouse management system takes care of the warehouse control and it increases the system complexity. Importance of a functional WMS is significant. Simulation is a solution to estimate and evaluate the functionality of the AS/RS already during the design phase.

In this work, the simulation follows the simulation study structure that was presented in Figure 2.2. The first step is problem formulation. The problem has been formulated as the research questions 2 and 3 in Subsection 1.3. Shortly, the problem is that the example AS/RS is complex system and functionality of it needs validation already during the design phase. The functionality will be tested in material flow simulations and in sensitivity analysis simulations.

The second step of a simulation study is data collection and model definition. In this work, the data collection step is included in previous subsections of Section 3. Because the system does not exist yet, detailed cycle times, speeds, delays etc. for the devices cannot be collected from a real system. Therefore, the relevant design material is introduced and utilized as modeling data. The model definition is pretty close to the design that was already introduced. Only a few simplifications will be made and those will be presented in Subsection 3.4.2.

The third step of a simulation study is the first validation. The validation is made in co-operation with stakeholders of the AS/RS development project during the simulation work. The stakeholders in this case are designers and customer of the AS/RS. The scope of the validation is to make clear that the so far made decisions and definitions are satisfying the stakeholders. Possible modifications to the study are easier to generate in the early phases of the project.

3.4.1 Modeling the design

As presented in Figure 2.2, the fourth step in simulation study is simulation model generation. The simulation model for this work was generated with commercial simulation software for discrete-event simulation. The strength of commercial simulation softwares is that usually those include ready-made objects that require only parameterization. Strength for commercial softwares is also that usually those provide graphical user-interface and visualization of the model. That typically makes the simulation easier for new users of the software. For example, references [36; 37; 43] provide instructions for choosing simulation software.

If earlier steps of a simulation are performed properly, then, the basic functionality of the simulated system should be already familiar. In the example AS/RS, the key features to familiarize are AGV connection and functionality of conveyors, industrial robots, stacker cranes, and packing stations. Detailed simulation requires also properties like speeds, accelerations, loading capacities etc. for the devices. If this information is not available, then, designer of the system is asked to give estimation about the parameters.

The model building may start when knowledge and data about the system is available. The simulation is an iterative process. System is modeled part by part and model should be continuously verified. Usually during the modeling, new questions about the system functionality arise [37, pp. 311]. Then, the system familiarization phase should be returned.

During the example AS/RS modeling, the work was divided in parts, so, that racking and stacker crane functionality were modeled first. Then, conveyor system with vertical conveyors was added. Lastly, AGV connection and packing stations were modeled. The modeling included continuous pilot runs that are mentioned in the fifth step in a simulation study that was presented Figure 2.2. However, some simplifications were made in the modeling. Those will be discussed next.

3.4.2 Simplifications

Model is always an imperfect imitation of a system. Also in the example simulation study, some simplifications were made. One simplification in the model is that the products are handled as product piles through the simulation. Size of a product pile is constantly 4 pieces of products. In the real system, the size of a product pile may vary between 1 and 5. This simplification is argued with two reasons. Firstly, more than 80 % of the products will be handled in piles of 4 products in the future system. Secondly, simulation times are faster. Handling piles instead of single products is less time consuming because simulated product objects amount is divided by four compared to the real system.

Another simplification is made in the storage channel modeling. In the real AS/RS, all of the channels will be 3 meters deep. The depth of the products will vary, so the amount of products that fit in the channel also varies. The AS/RS customer has stated that in the real system, maximum amount of products per channel will be 11.95 on average. This channel structure is simplified in the model so, that each channel has place for three piles of four products. Therefore, maximum load of a channel is always 12 products. This simplification is made because the commercial simulation software does not have option for the channel structure that shows up in the example AS/RS.

3.4.3 Production and order generation

To simulate the material flow through the example AS/RS, only one stock keeping unit (SKU) is utilized. This means that all of the products stored and retrieved are equal [44]. Because the storage strategy is random storage, the storage channels are evenly utilized even if there is only one SKU.

Production batches and orders for the simulation model are constant sized. A single production batch is always 24 pieces of products. The size for the batch is same as maximum load of an AGV if each of the 6 product piles consists of 4 pieces of products. Order size is always 48 pieces of products. The AS/RS customer has told that 48 is the average size of the orders from the future AS/RS.

Timestamps for the production batches and orders are generated randomly. The data generator is informed that how many pieces of products are required to place to or pick from the AS/RS per every half an hour. Then, the generator generates timestamps randomly for each production batch and order. The distribution to half an hour periods is used because in each simulation run there will be warm-up and cool down periods of half an hour. Therefore, it is ensured that during every half an hour period production and order amounts are the designed.

The scope of this work is in simulation and analysis of the material flow through the example warehouse. To simulate the material flow through the warehouse, infeed production and outfeed order generation are simplified from the real system. Therefore, detailed production and order data analysis is not in the scope of this work.

4. EXPERIMENT

In this section the performed experiment will be introduced. According to Figure 2.2, the seventh step in simulation study is experiment designing. In this work, the experiment will be divided into two kinds of simulations: material flow simulations and sensitivity analysis simulations. In subsection 4.1, experiment of simulating the material flow through the example AS/RS will be introduced. With the material flow simulations, the designed layout and AS/RS functionality can be tested and validated. Also the uncertainties of the system will be introduced. The uncertainty is parameters and features of the model that are not yet designed and determined in details. The uncertainties will be discussed in Subsection 4.2. The significance of the uncertain parameters and features will be analyzed with sensitivity analysis. In the sensitivity analysis, uncertain parameters will be varied and effect on chosen output parameters will be simulated. Sensitivity analysis experiment will be presented in Subsection 4.3.

4.1 Material flow simulations

Design for the example AS/RS was presented in Section 3. Also receiving and picking requirements for the AS/RS were presented in Table 3.1. With simulation runs, the warehouse functionality will be tested with varying infeed and outfeed amounts. AS/RS storing and delivering amounts will be varied between the promised average and maximum values. The infeed and outfeed amounts will be varied according to Table 4.1.

Table 4.1 *Values for infeed and outfeed amounts.*

Infeed amounts per hour	Outfeed amounts per hour
624	1344
1056	1824
1440	2304
1872	2880
2304	3360

The material flow simulations will be performed for 25 different combinations of infeed and outfeed amounts that are presented in Table 4.1. Five simulation runs for each combination will be performed. Specification of the infeed and outfeed amounts and amount of simulation runs is presented in Table 4.2.

***Table 4.2** Specification of infeed, outfeed and simulation run amounts in material flow simulations.*

Parameter	Value	Note
Different infeed values	5	
Different outfeed values	5	
Infeed – outfeed -combinations	25	*5 infeed values * 5 outfeed values*
Simulation runs per combination	5	
Simulation runs in total	125	*5 runs * 25 combinations*

The length of each simulation run will be 3 hours. In the beginning of each simulation run, there will be warm-up period of 30 minutes. After the warm-up period, statistics measurements and counters will be reset to zero. Then, simulation will continue for 2 hours and statistics are collected. Statistics collection will end after 2.5 hours of the simulation has advanced. The last 30 minutes will be so called cool down period. The purpose of the warm-up and cool down periods is that during the statistics collection there should be infeed and outfeed available. Then, the results are more reliable because also in real life, the system will be continuously utilized.

The promised receiving and picking values for the example AS/RS were calculated with storage utilization of 50 %. The maximum filling capacity of the warehouse is 529 920 pieces of products. Therefore, the warehouse filling amount is 264 960 pieces of products in begin of the simulations. This start inventory will be distributed to the warehouse according to the random storage strategy that was introduced in Subsection 3.3.

Realized infeed and outfeed amounts and device utilization ratios will be the focused performance measurements in the material flow simulations. Utilization ratios of stacker cranes and industrial robots will be considered. With simulation, it is possible to detect if higher capacities for the devices are required.

4.2 Uncertainties

As presented in Subsection 2.2, modeling uncertainties are caused by the assumptions that are required during a simulation study. Assumptions are related to all levels of the system from detailed device parameters to features of the factory control systems. Modeling system under design and development includes more uncertainty than system that already exists. The example AS/RS is in development phase, and therefore, uncertainty causing assumptions are required.

The stakeholders of the simulation study have identified three parameters in the system causing uncertainty. Parameters are industrial robot movement times, stacker crane delays, and storage utilization. Those three parameters are also chosen to be analyzed in this work in more details. With sensitivity analysis, significance of the chosen uncertain parameters will be assessed.

4.2.1 Industrial robot movement times

Movement time of industrial robot means the time that robot requires to move from position to another. Positions are infeed conveyor, lower outfeed conveyor, higher outfeed conveyor, infeed holder, and outfeed holder. Movement times include uncertainty because the pile gripper in the example AS/RS is never used before. Therefore, it is not certain that how fast the gripper can pick, move, and place product piles.

The assumed movement times of industrial robots are introduced in Table 3.4. To reach the presented times, maximum speed and acceleration of the industrial robots is required. However, it is possible that maximum speed and accelerations can not be utilized. This is the reason, why the system functionality should be tested with higher robot movement times.

On the other hand, the system functionality will be tested with smaller robot movement times. It is possible that the industrial robots could be faster if the trajectories are still optimized or robots are changed to faster ones. Simulation with smaller robot movement times will also give wider overview to the significance of the robot movement times to the system capacity.

Different movement times of industrial robots are introduced to the simulation model as coefficient that scales all of the movement times smaller or higher. The coefficients utilized in the simulation are presented in Table 4.3.

Table 4.3 *Coefficients utilized to scale robot movement times higher.*

Movement time scaling coefficient
0.7
0.8
0.9
1.0
1.1
1.2
1.3

The coefficients in Table 4.3 are utilized so, that whole robot movement time table (Table 3.4) is multiplied by one of the coefficients. Then, the effect of changed movement times will be assessed. This procedure is performed with all of the coefficients.

4.2.2 Stacker crane delays

Work cycle for a stacker crane was introduced in Subsection 3.2. In the work cycle, there are two kinds of delays: delay for positioning and delay between the fork moves. Positioning means the time between stacker crane stops close to the channel and starts the first fork move. Before the first fork move, stacker crane must be accurately positioned to ensure that loading and unloading position is precise. This avoids product and device damage. Average delay for the positioning is assumed to be 12 seconds. This positioning delay is not certain value and effects of it variation should be assessed.

Another parameter that is causing uncertainty in the stacker crane work cycle is delay between the fork moves. This delay is required to make sure that fork and products are completely stationary before the next move. It makes the following move safer and product and device damages are avoided. The required delay varies, for example, based on the handled products. If handled products are labile, then, longer delay is required. In the example AS/RS, delay between the fork moves is assumed to be 2 second. This delay is required three times per cycle, so the total delay is 6 seconds. This value is not certain, and therefore the impacts of the value variation will be tested.

Delay for positioning and delay between the fork moves is introduced to the model as constant value that repeats in every work cycle. The assumed total delay is 18 seconds (12 s + 6 s). The designers of the AS/RS have stated that this value can be either smaller or greater in the real system. The total delay will be varied between – 50 % and + 100 % compared to the assumed 18 seconds. The utilized delay values are in Table 4.4.

Table 4.4 *Variation of stacker crane total delay.*

Change of total delay in %	Value of total delay (s)
– 50 %	9
– 25 %	13.5
0 %	18
+ 25 %	22.5
+ 50 %	27
+ 75 %	31.5
+ 100 %	36

The difference between minimum and maximum delays is 27 seconds. The difference is quite big but is worth testing that how the system is affected by various delay values. Thus, the understating of the system will get better.

4.2.3 Storage utilization

Storage utilization means percentage of the storing capacity that is in use [40; 45]. In this work, storing capacity is defined to be only the space of storing channels. For example, space of forks on stacker cranes, conveyors or other devices is not counted as warehouse capacity.

Storage utilization may vary during the warehouse is used. Variation bases on seasonal or other changes in supply and demand of stored goods. For example, the storage utilization must probably be higher before season of higher demand begins. Warehouse must be functional in spite of the changes in storage utilization. And more importantly, it must be known that at what level of storage utilization the warehouse becomes non-functional. [37; 45]

The scope of the simulation experiment is to vary the storage utilization and to assess, how variation affects the AS/RS functionality. Storing capacity of the example AS/RS is 529 920 pieces of products. Storage utilization is varied as presented in Table 4.5.

Table 4.5 *Storage utilizations in the simulation experiment.*

Storage utilization (%)	Amount of stored products
5	26 496
20	105 984
35	185 472
50	264 960
65	344 448
80	423 936
95	503 424

In practice, the storage utilization will be introduced to the simulation model as start inventory. The model will get the start inventory amount according to the “Amount of stored products” -column in Table 4.5. Before a simulation run starts, the simulator distributes the start inventory based on the random storage strategy that is used also through the simulation.

4.3 Sensitivity analysis

Sensitivity analysis means variation of model input variables and analyzing the effects on output variables. This work focuses on analyzing the significance of the uncertain parameters that are robot movement times, stacker crane delays, and storage utilization. The analyzed output parameters will be average utilization ratios of industrial robots and stacker cranes, and realized infeed and outfeed amounts.

In the sensitivity analysis, the uncertain parameters will be varied according to Table 4.3, Table 4.4, and Table 4.5. Therefore, there will be three different simulation setups and each of the uncertain parameters will be varied in own setup. Each uncertain parameter has 7 chosen values around the assumed parameter value. For each parameter value, 5 individual simulation runs will be performed. Therefore, there will be 35 (7 parameter values * 5 runs) simulation runs per setup. The whole sensitivity analysis consists of 105 (3 different parameters * 35 runs) individual simulation runs.

Data will be collected the same way as in the Subsection 4.1 was described. So, the simulation runs will last for 3 hours and there is warm-up and cool down periods of half an hour each. Then, the infeed and outfeed amount values will be scaled to pieces per hour unit.

The production and order data will be generated as it was described in Subsection 3.4.3. The designed infeed and outfeed amounts will be the maximum values in all of the simulations. This means that target infeed amount is 2304 pieces of products per hour and target outfeed will be 3360 pieces of products per hour. In the maximum amount simulations the sensitivity of the system is possible to observe.

5. RESULTS

The results of this work will be presented in this section. In the first subsection the requirements for the simulation platform are listed. Then, the results of material flow simulations will be presented in the second subsection. In the third subsection the results of sensitivity analysis will be introduced. The execution of material flow simulations and sensitivity analysis were presented in Section 4. This section will also go through steps 9 and 10 of simulation study that were presented in Figure 2.2. The steps are output data analysis, and result documentation and presentation.

5.1 Requirements for the simulation platform

To simulate and analyze the example AS/RS, which was introduced in Section 3, the simulation platform needs to fill several requirements. The requirements are separated to five categories that are *general requirements*, *modeling the devices*, *production and order generation*, *warehouse management system*, *and performance measurements*.

General requirements:

- **Flexibility**: The simulation platform needs to allow modeling various types of systems. [46]
- **Transparency**: The platform and model user needs to fully understand that how the simulation model works. [46]
- **Quality assurance**: Confirmation that the model provides correct answers. [46]
- **Efficiency**: The simulations should be performed in tolerable time without unreasonable investments on computer hardware. [46]

Modeling the devices:

- **Speed**: Modeling the speed of devices (conveyors, stacker cranes, AGVs) is required. For some devices speed to three dimensions (X, Y, and Z) is required. Also different speed with and without load is required to be modeled.
- **Acceleration**: Modeling the acceleration of devices is required. Acceleration may vary in three dimensions. Acceleration may vary also if device is loaded or unloaded.
- **Loading capacity**: Loading capacity of devices varies. For example, length of the conveyors affects the loading capacity.
- **Length**: The length of aisles and conveyors varies.
- **Different conveyor types**: In the example AS/RS, there are four different conveyor types that were introduced in Subsection 3.2. Possibility for modeling the different conveyor types is required.

- **Movement time**: The industrial robots have capacity informed as movement times between various positions.
- **Positioning time**: The stacker cranes have positioning time that is required to wait before stacker crane can operate into a channel.
- **Processing time**: Packing stations have operating time informed as processing time. Ability for modeling this kind of processors is required.

Production and order generation:

- **Pile**: Products are handled as piles, so the platform has to be able to handle product piles.
- **Production batch**: Production is informed to the model as batches of 24 pieces of products. The platform is required to work with this kind of batches.
- **Order**: Orders are sets of 48 products. The platform needs to understand and fill this kind of orders.
- **Randomization**: Production and order times need to be generated randomly based on designed infeed and outfeed amounts.

Warehouse management system:

- **Pile routing**: Routing of product piles need to be possible. The routing is important especially in the conveyor system, AGVs, industrial robots, and packing stations.
- **Storage strategy**: Random storage strategy is required.
- **Task allocation**: The tasks for different devices need to be allocated automatically.
- **Production batch and order handling**: WMS has to be able to handle production batches and orders.

Performance measurements:

- **Realized infeed and outfeed amounts**: There should be measurement about how much production is stored to the AS/RS and how much products are retrieved from the system.
- **Device utilization ratios**: Measurement of device utilization ratios is required.
- **Flexible data handling**: Working with the performance data should be flexible.

5.2 Material flow simulations

In the material flow simulations the scope is on assessing the system functionality with varying infeed and outfeed amounts. The results of the simulations will be introduced in two subsections. In the first subsection the realized infeed and outfeed amounts will be presented and in the second subsection the device utilization ratios will be visualized.

5.2.1 Realized infeed and outfeed amounts

The utilized infeed and outfeed amount values were presented in Table 4.1, and in Table 4.2, specification of parameter combinations and simulation run amounts were introduced. There are 25 infeed and outfeed amount combinations (5 infeed values * 5 outfeed values) and for each combination, five simulation runs were performed. Therefore, 125 individual simulation runs were performed. The averages of the realized infeed amounts are in Table 5.1.

Table 5.1 *Averages of the realized infeed/h amounts.*

<table>
<tr><th colspan="2" rowspan="2">Average realized infeed amount</th><th colspan="5">Designed infeed amounts</th></tr>
<tr><th>624</th><th>1056</th><th>1440</th><th>1872</th><th>2304</th></tr>
<tr><td rowspan="5">Designed outfeed amounts</td><td>1344</td><td>624</td><td>1057</td><td>1440</td><td>1872</td><td>2290</td></tr>
<tr><td>1824</td><td>624</td><td>1056</td><td>1438</td><td>1855</td><td>2312</td></tr>
<tr><td>2304</td><td>624</td><td>1057</td><td>1442</td><td>1858</td><td>2294</td></tr>
<tr><td>2880</td><td>624</td><td>1054</td><td>1432</td><td>1875</td><td>2308</td></tr>
<tr><td>3360</td><td>624</td><td>1054</td><td>1438</td><td>1870</td><td>2323</td></tr>
</table>

Average infeed amount of five individual simulations per infeed and outfeed combination is always pretty close to the designed value. The difference as percents vary between – 1.0 % and + 0.8 %. The reason for the variation is in the capacity of the infeed conveyor system. If less infeed and/or outfeed are available, then, the products get never in jam and 100 % of the products can be fed to the warehouse. However, if more infeed and/or outfeed are available, then, the conveyor system may get stuck for a while and this leads to variation in realized infeed amounts. If the system get's stuck at some point during the simulation, then, exactly designed amount of products is not fed in to the AS/RS. This variation in infeed amounts should be considered when device utilization ratios will be assessed. If infeed amount is greater than designed value, then, the device utilization ratios are higher and vice versa.

In Table 5.2, averages of the realized outfeed amounts are presented. Also these results are averages of five individual simulation runs per each infeed and outfeed combination.

***Table 5.2** Averages of the realized outfeed/h amounts.*

Average realized outfeed amount		Designed infeed amounts				
		624	1056	1440	1872	2304
Designed outfeed amounts	1344	1328	1372	1302	1371	1331
	1824	1815	1838	1862	1864	1838
	2304	2289	2291	2304	2307	2331
	2880	2858	2864	2870	2823	2803
	3360	3419	3316	3291	3292	3052

The results in Table 5.2 present that realized outfeed amounts vary more compared to the realized infeed amounts. Outfeed amounts vary as percents between – 9.2 % and + 2.1 % compared to the designed values. The reason for this variation is in the WMS that is controlling the AS/RS. WMS makes individually decisions when the orders are filled. This leads to the result that the realized outfeed amounts vary compared to the designed values.

In the simulations where the designed infeed amount is 1440 or greater and designed outfeed amount is 2880 or greater, the realized outfeed amount is generally lower than designed. This is resulting from the reason that industrial robots are prioritizing the incoming products over outgoing products. Then, the devices do not have enough capacity to fulfill the orders.

The realized outfeed amount is smaller than the designed value especially in the case when infeed and outfeed amounts reach the peak values. In general, this combination is interesting because the system should be functional also with the highest infeed and outfeed amount combination. Therefore, results of each 5 individual simulation run with the maximum infeed and outfeed amounts are presented in Table 5.3.

***Table 5.3** Realized infeed and outfeed amounts when designed infeed and outfeed amounts are the peak values. Designed infeed = 2304 and designed outfeed = 3360.*

Realized amount	Maximum infeed and outfeed simulation run index				
	1.	2.	3.	4.	5.
Infeed	2328	2322	2336	2328	2304
Outfeed	2992	2894	3142	3040	3192

According to the results in Table 5.3, the outfeed amount was closest to the designed value in simulation Run 5. In that run also infeed amount was exactly same as the designed. On the other hand, the outfeed is 466 pieces of products smaller per hour than the designed in Run 2. Even realized infeed amount do not explain the result because it is pretty close to the designed value. The reason for the variation in the realized infeed and outfeed amounts is in random production and order generation. It causes that production and orders are not continuously available, and then, the devices are not all the time utilized and throughput is smaller. To understand the system functionality deeper, the following subsection will focus on the device utilization ratios in the different simulation scenarios.

5.2.2 Device utilization ratios

The devices that will be assessed are stacker cranes and industrial robots. All of the devices are equally utilized, and therefore, the results will be average utilization ratios of all same category devices. The data sets used to visualize the device utilization ratios are available at Appendix A. The first device to be considered is stacker crane. Average utilization ratios of the stacker cranes are in Figure 5.1.

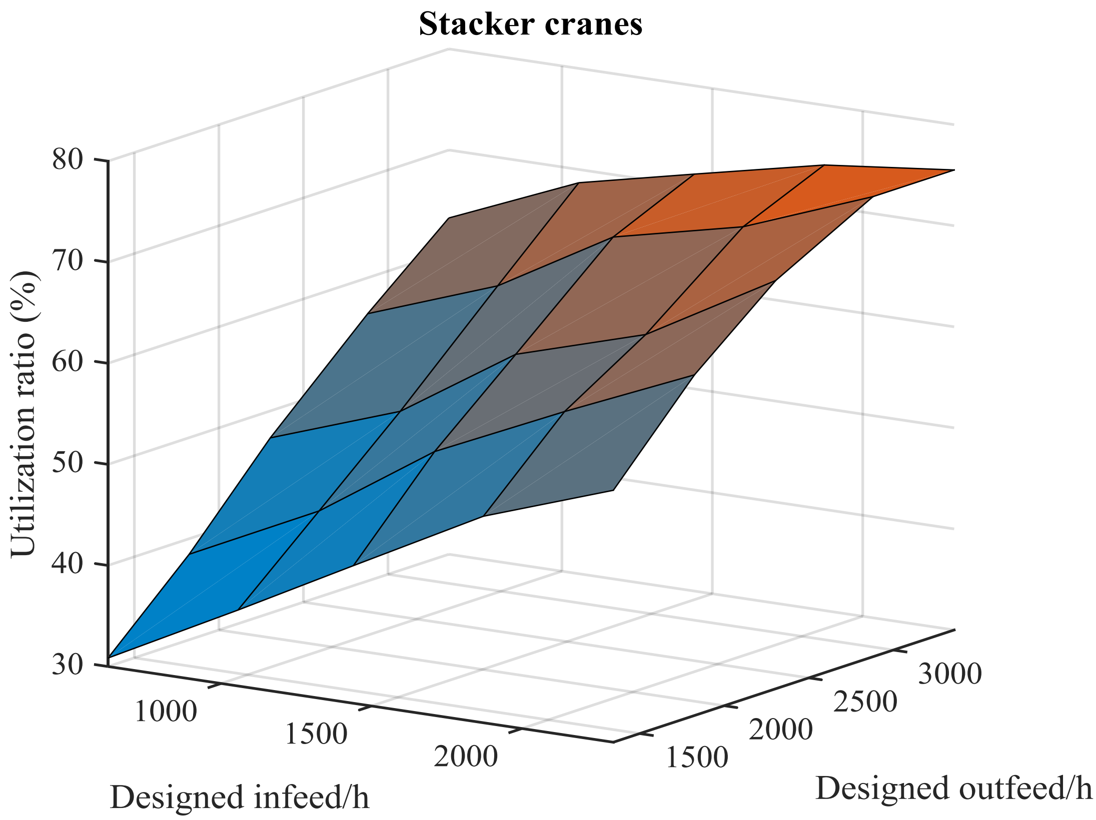

Figure 5.1 *Average utilization ratios of the stacker cranes.*

The average stacker crane utilization ratios vary between 30.8 % and 75.5 %. As presented in Figure 5.1, the utilization ratio is higher when infeed and outfeed amounts are higher. However, the surface is flatter when the infeed and outfeed amounts reach the peak values. The explanation for this is that the realized outfeed amount is less than the designed during the peak amount simulations. Because the stacker cranes have 25 % of the capacity left during the peak amount simulations, it seems that the stacker cranes are not the bottleneck of the system.

The second device to be considered is industrial robot. Average utilization ratios of the industrial robots are in Figure 5.2.

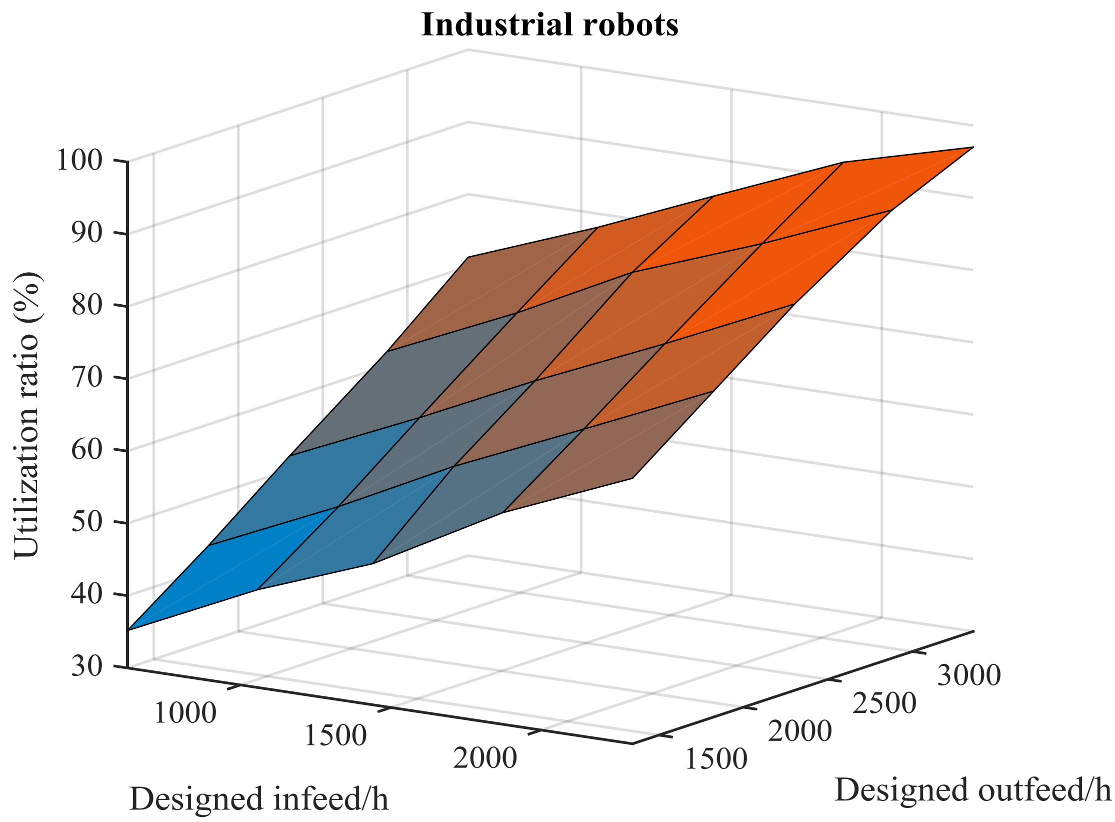

Figure 5.2 *Average utilization ratios of the industrial robots.*

As presented in Figure 5.2, the average utilization ratios of industrial robots vary between 35.2 % and 97.0 %. The utilization ratio gets higher when the infeed and outfeed amounts get higher. The surface is close to plane but it is bent a bit close to the infeed and outfeed peak amounts. This is again caused by the realized outfeed amount that is 9.2 % smaller than the designed.

Utilization ratio 97.0 % is high. It tells that the industrial robots have had only 3 % of free time when the infeed and outfeed amounts have reached the maximum. Therefore, it is possible that the industrial robots are the bottleneck of the system. The sensitivity analysis will confirm this assumption. Before the sensitivity analysis, the device utilization ratios of all 5 simulation runs with the maximum infeed and outfeed amounts will be presented. The results are in Table 5.4.

Table 5.4 *Device utilization ratios when designed infeed and outfeed amounts are the peak values. Designed infeed =2304 and designed outfeed = 3360.*

Utilization ratio (%)	Maximum infeed and outfeed simulation run index				
	1.	2.	3.	4.	5.
Stacker cranes	76.18	76.67	74.95	75.45	74.69
Industrial robots	96.55	94.74	98.26	96.86	98.62

According to Table 5.4, the utilization ratios of industrial robots vary between 94.74 % and 98.86 %. If results of Table 5.3 and Table 5.4 are compared, it is possible to conclude that utilization ratio of industrial robots is higher when sum of realized infeed and outfeed amounts is higher. The utilization ratios of stacker cranes vary between 74.69 % and 76.67 %. The results in Table 5.4 present that the stacker crane utilization ratio is lower when utilization ratio of industrial robots is higher. The reason for this is that when the industrial robot is more utilized, it is more probable that stacker crane has to wait for the industrial robot. Then, the utilization ratio of stacker crane is lower.

5.3 Sensitivity analysis

In the sensitivity analysis, uncertain parameters (robot movement times, stacker crane delays and warehouse utilization) will be varied according to tables presented in Subsection 4.2. The assessed output values will be realized infeed and outfeed amounts, and utilization ratios of stacker cranes and industrial robots.

The first parameter to be varied is robot movement time. The variation will be performed via a scaling factor that will scale all of the robot movement times higher or lower compared to the assumed values. The results are presented in Figure 5.3.

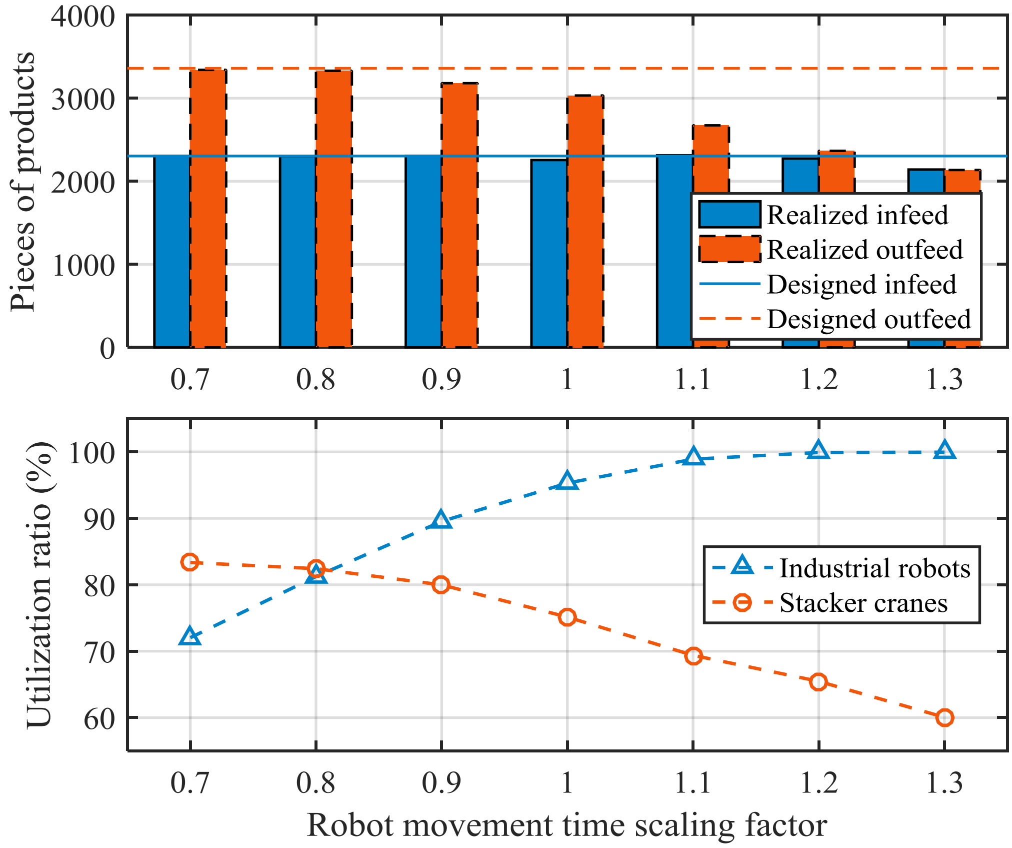

Figure 5.3 *The effect of robot movement time variation on output variables.*

As presented in Figure 5.3 and already in Subsection 5.2, the designed outfeed amount is not reached when the robot movement time scaling factor is 1.0. But, when the robot movement times are scaled to be smaller enough, also the designed outfeed amount is reached. In the simulations where the scaling factor is equal to or lower than 0.8, the designed outfeed amount is reached. However, when the scaling factor get higher than 1.0, the realized outfeed amounts drop significantly.

The realized infeed amount is not affected by the robot movement scaling factor when the factor varies between 0.7 and 1.2. The reason is that the industrial robots prioritize infeed over outfeed to avoid blocking at the infeed conveyors. However, when the robot movement times are 30 % higher than the assumed, also the realized infeed amount drops a bit. This tells that the infeed conveyor gets stuck at some point of the simulation. The reason for the jam is that the waiting area get's full of products. Then, the industrial robots cannot prioritize infeed over outfeed anymore because the outfeed waiting area must be refilled.

The robot movement times are affecting the robot utilization ratios. If slower device has to perform the same amount of moves as faster device, it takes more time and utilization ratio is higher, and vice versa. When the scaling factor is 0.7 or 0.8, the utilization ratio of the industrial robots is less than 85 %. This informs that the industrial robots could move even more pieces of products, if more production or/and orders were available.

However, when the scaling factor is greater than 1.0, the utilization ratio of industrial robots is almost 100 %. This means, that all of the industrial robots are almost continuously working.

The utilization ratio of stacker cranes is changing according to the total amount of products stored to and retrieved from the warehouse. When more products are stored and retrieved, the utilization ratio is higher, and vice versa. Utilization ratio of the stacker cranes is around 82 % when the designed infeed and outfeed amounts are reached. This tells that the stacker cranes make handling the maximum infeed and outfeed amounts possible.

The second parameter to be varied is total delay of stacker crane work cycle. The work cycle and delay were explained in Subsections 3.2 and 4.2.2. The assumed value of the total delay is 18 seconds and in the sensitivity analysis simulations the value will be varied between 9 and 36 seconds. The results are in Figure 5.4.

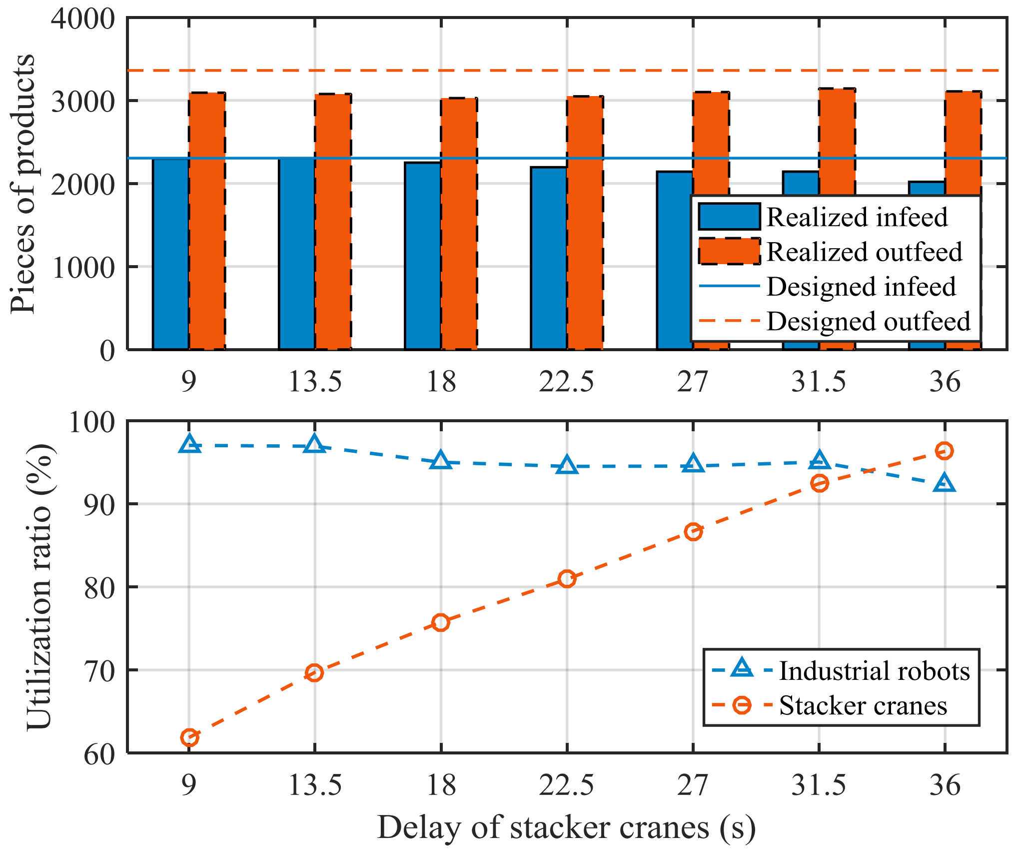

***Figure 5.4** The effect of stacker crane delay variation on output variables.*

As presented in Figure 5.4, the realized infeed amounts are close to the designed value when total delay of stacker cranes is equal to or lower than the assumed 18 seconds. When the delay is higher than the assumed value, the realized infeed amounts drop slightly. The reason for this is that the infeed conveyor gets stuck at some point, because the stacker cranes do not refill the infeed waiting area fast enough. Then, the industrial robots cannot place products to the infeed waiting area and jam at infeed conveyor is possible.

The realized outfeed amounts are constantly a bit over 3000 pieces of products. They are not affected by the total delay of stacker cranes. The reason for this is that the maximum utilization ratio of stacker cranes is never reached. Therefore, the stacker cranes can take care of the amount of retrieved products that the industrial robots can handle. If the total delay was even higher than 36 seconds, then, the outfeed amount of more than 3000 probably would not be reached.

The utilization ratio of stacker cranes changes according to the total delay. If the total delay is higher, then, also the utilization ratio is higher, and vice versa. Even if the total delay is twice as high as the assumed value, the maximum utilization ratio is not reached. However, if the industrial robots would be faster and the realized outfeed amounts were higher, then, probably the total delay of 36 seconds could be too high. The result could be that the stacker crane changes to be the bottleneck of the system. This kind of analysis will be discussed in Section 7 in more details.

The utilization ratio of industrial robots changes according to the total amount of stored and retrieved pieces of products. When the total amount is higher, the utilization ratio is higher, and vice versa. The utilization ratio of stacker cranes vary between 92 % and 97 %, so the utilization ratios are quite high. However, there is some capacity left that could increase the total amount of stored and retrieved products.

The third uncertain parameter to be varied is warehouse utilization. Warehouse utilization means the amount of products in warehouse in the beginning of a simulation run. The material flow simulations were performed so, that the warehouse utilization was 50 %. In the sensitivity analysis simulations this value is varied between 5 % and 95 %. The results of the simulations are presented in Figure 5.5.

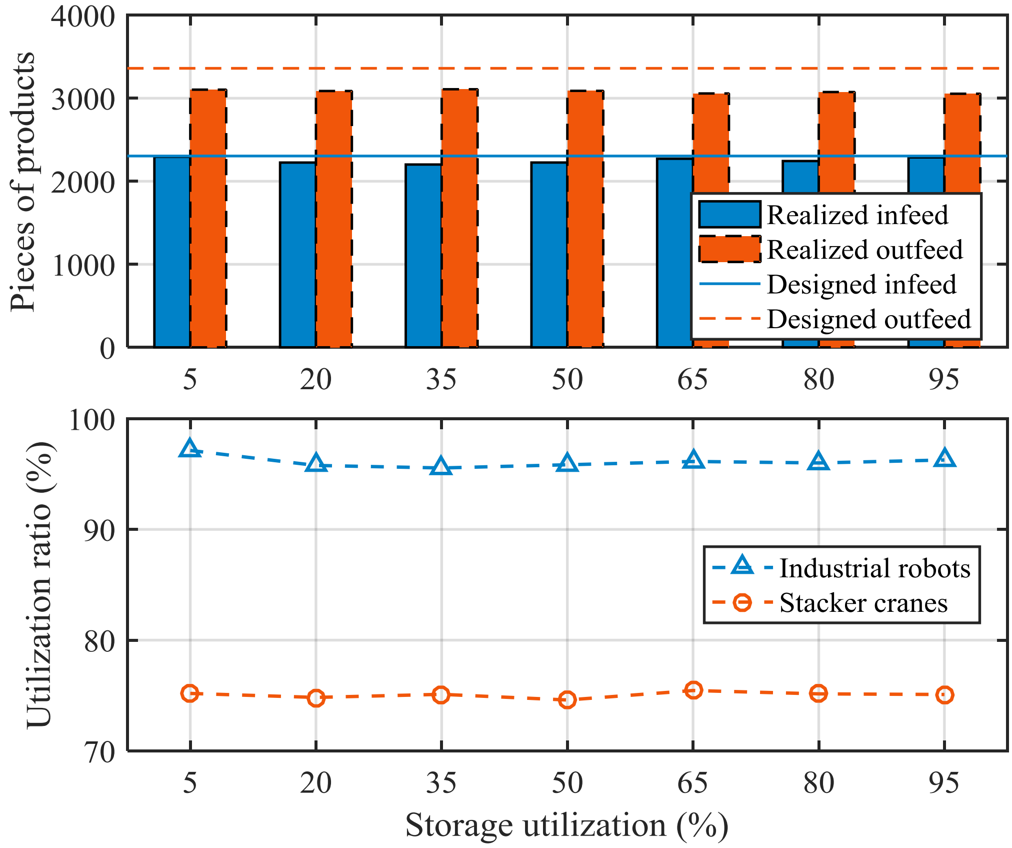

***Figure 5.5** The effect of storage utilization variation on output variables.*

As presented in Figure 5.5 the realized infeed and outfeed amounts are almost constant even if the storage utilization varies. The realized infeed amount is always close to the designed value 2304, and the realized outfeed amount is always a bit more than 3000 pieces of products. Also the device utilization ratios stay almost constant in all of the simulations. The utilization ratio of industrial robots is always close to 95 %, and utilization ratio of stacker cranes is close to 75 %.

The reason for the almost constant output values is in the utilized storage strategy that is random storage. The random storage strategy makes sure that the products are stored to and retrieved from all around the warehouse. Therefore, the warehouse will be evenly utilized. It is one of the main strengths of random storage strategy that the functionality of AS/RS is possible to predict even if storage utilization varies.

The almost constant infeed and outfeed amounts and utilization ratios also tell that the warehouse never gets completely full or empty. If the warehouse gets full, drop in infeed amount would be sign of that. On the other hand, if the warehouse gets empty, drop in outfeed amount would tell about it. The requirement for fluent AS/RS functionality is that there are always products available but there is also space for new products.

6. DISCUSSION

In the discussion part of this work, the research questions will be answered according to the results presented in Section 5. The results will also be discussed and evaluated in more details. The research questions were introduced in Subsection 1.3.

The first research question deals with the requirements for simulation platform to simulate an AS/RS. The identified requirements were listed in Subsection 5.1. The requirements were distributed to five different categories that are *general requirements*, *modeling the devices*, *production and order generation*, *warehouse management system*, *and performance measurement*.

The general requirements aim to simulation platform that allows construction of understandable and user-friendly models. The modeling also needs to be flexible. Already AS/RSs can vary quite a lot compared to each others but it should not be limit for the modeling. The model also needs to generate correct answers and results in tolerable amount of time. The platform probably can not detect all of the user generated modeling mistakes in the model but the platform should not generate own errors to the model.

Modeling various devices should be possible with the simulation platform. Already in the example AS/RS there is more than five completely different device types. Different device types have their own requirements that are basically related to modeling the capacity and processing time of the devices. The simulation platform should include general base models of different devices that can then be detailed to fill the precise requirements.

Production and order generation is utilized to inform the AS/RS that how much products it has to store and retrieve. Variation of the infeed and outfeed amounts should be flexible because in the simulation runs the amounts are varied. The WMS takes care of handling the material flow. The WMS is the brain of an AS/RS so precise modeling of WMS is important. The key tasks for WMS are routing the product piles, allocating devices, delivering the ordered products, and storing the incoming products.

When the system is modeled on the decided level of realism, the performance measuring becomes topical. In this work, the performance measurements are device utilization ratios and realized infeed and outfeed amounts. Therefore, measuring these variables should be possible. Also flexible working with the results should be possible. This means, for example, moving the results to different analysis softwares as CSV or XLS-files.

The second research question considers the performance of the example AS/RS when the designed infeed and outfeed amounts are varied between their average and maximum values. The observed performance measurements are realized infeed and outfeed amounts, and utilization ratios of industrial robots and stacker cranes.

The realized infeed amounts are always quite close to the designed values even if designed infeed and outfeed amounts reach their peak values. The reason for this is in logic controlling the industrial robots. The industrial robots are prioritizing infeed over outfeed. Always when there is infeed available and space at the waiting area, the industrial robot moves incoming products to waiting area. Therefore, the infeed conveyor does not get stuck and designed infeed amounts can be reached.

The realized outfeed values reach the designed values when the designed infeed and outfeed amounts are low enough. However, when the designed infeed and outfeed amounts reach their maximum values, the designed outfeed amounts can not be reached. This tells that the system can not reach the designed capacity. The reason for this can be identified from the device utilization ratios.

The utilization ratios of industrial robots vary between 35 % and 97 %. When the designed infeed and outfeed amounts are higher, also the utilization ratios of industrial robots are higher, and vice versa. The utilization ratio of 97 % is really high. It tells that, on average, industrial robots are free only for 3 % of the simulation time. To make the system reach the maximum infeed and outfeed amounts, higher capacity for the industrial robots is required. It would make the system also more reliable if there was a bit extra capacity.

The utilization ratios of stacker cranes vary between 30 % and 76 %. Also in case of stacker cranes, the utilization ratio is higher if designed infeed and outfeed amounts are higher, and vice versa. The utilization of the stacker cranes would be higher if the maximum outfeed amount was reached. However, the stacker cranes have enough capacity to fill the designed requirements.

The third research question is concerning to the sensitivity of the AS/RS with respect to the variables causing uncertainty in the system. The uncertain variables are robot movement times, total delay of stacker cranes and warehouse utilization. The observed performance variables are realized infeed and outfeed amounts, and utilization ratios of industrial robots and stacker cranes. In the sensitivity analysis simulations the designed infeed and outfeed amounts are the maximum values. The sensitivity analysis is performed so that the uncertain parameters are varied and the effect on the performance variables is analyzed.

The example AS/RS is sensitive for variation of the robot movement times. If the times are decreased for 20 % or more, the system can reach the designed infeed and outfeed amounts. But if the movement times are greater than the assumed value, the realized outfeed amounts drop significantly. This confirms that the industrial robots are the bottleneck of the system. Therefore, the industrial robots would require more capacity if the maximum infeed and outfeed amounts are required to be reached.

Based on the results, the example AS/RS is only a bit sensitive for the variation in the total delay of stacker cranes. The realized infeed amounts decrease slightly if total delay is increased. The reason for this is that the infeed conveyor gets stuck at some point of the simulation if the stacker cranes have too high delays. However, the variation is not significant. The stacker cranes have so much extra capacity that those are not the bottleneck of the system even if the assumed delay is doubled.

The results present that the AS/RS is not at all sensitive for the variation of warehouse utilization. The warehouse utilization is varied between 5 % and 95 % but there is no effect on the performance measurements. This is one of the greatest strengths of the random storage strategy. The warehouse is evenly utilized in spite of the warehouse utilization. Therefore, predicting the AS/RS functionality is easier if random storage strategy is utilized.

7. CONCLUSIONS AND FUTURE WORK

The conclusions of this work will be presented in this section. Also potential future work related to simulation and analysis of AS/RSs will be introduced in Subsection 7.2. When assessing the results of this work, it is good to note that this work focuses only to one example AS/RS and to a few features of it. Therefore, simulation and analysis of other AS/RSs will probably need some different steps to perform a simulation study. But, the general structure of the simulation study presented in this work should be applicable also in future studies.

7.1 Conclusions

AS/RSs can be complex systems. The reasons for this complexity can be, for example, warehouse size, aisle amount, high capacity requirements, and several stacker cranes moving on same aisle. On the other hand, an AS/RS development project from the first offer to the final commissioning can take even several years. Therefore, there is a need for solution that helps the stakeholders of the development project to understand and validate that how the designed system actually works. The solution offered in this work is simulation of an AS/RS.

The scope of this work was in simulating the example AS/RS. The AS/RS consists of stacker cranes, industrial robots, high bay racking, conveyor system, and packing stations. The products in the racking are stored behind each other, so, the simulated AS/RS has deep channels. These features and high capacity requirements make the simulated AS/RS to be complex system.

The simulation study follows the steps presented in Figure 2.2. The first step is formulating the problem that is tried to solve with the simulation. The problem in this work is formulated as the research questions. The scope of the work is in material flow simulations, sensitivity analysis, and requirements for the simulation platform. When the problem is formulated, data collection and model definition begins. The results of this phase are collected in the Section 3. Then, the actual modeling may begin. The example AS/RS is modeled with platform for discrete-event simulation.

When the model was constructed, the simulation experiments were designed. Two different kinds of simulations were performed in this work. They were material flow simulations and sensitivity analysis simulations. In the material flow simulations, designed infeed and outfeed amounts were varied. The purpose of these simulations was in getting an overview of the system functionality. The system functionality was presented as performance measurements that were realized infeed and outfeed amounts, and utilization ratios of stacker cranes and industrial robots. In the sensitivity analysis simulations, three uncertain parameters were varied and effect on performance values was analyzed. The uncertain parameters were robot movement times, stacker crane delays, and warehouse utilization. The performance measurements were realized infeed and outfeed amounts, and utilization ratios of stacker cranes and industrial robots.

The results of the simulation runs were presented in Section 5. The main result was that currently the industrial robots are the bottleneck of the system. In the maximum amount simulations, industrial robots have only 3 % of free time on average and the maximum outfeed is not reached. With better routing of piles also the rest 3 % could be utilized but the system functionality would not be reliable if all of the capacity was utilized. To make the system reliable and reach the designed infeed and outfeed amounts, some extra capacity would be required.

In addition to the performance measurements, the simulation gives a wide understanding and overview of the example AS/RS. With the simulation it is possible to present the system functionality to the stakeholders of the AS/RS development project. At its best, the simulation can even clear misunderstandings between the stakeholders. This can save a lot of time and money during the commissioning phase.

In general, there are several ways how this simulation work enables financial savings in AS/RS development project. The main financial benefit is the support for choosing devices with appropriate capacities. With sensitivity analysis, it is possible to find out that how much capacity is actually required. In the example AS/RS, the stacker cranes have some extra capacity because the utilization ratios vary around 76 % in maximum infeed and outfeed amount simulations. Therefore, the capacity of stacker cranes could be even lower and this would save money. However, industrial robots do not have enough capacity, so more optimization or investment on devices with higher capacity is required.

The next most significant financial benefit is the chance for spotting errors and bottlenecks in the designed system during the design phase. If an error or bottleneck is detected in a real physical system, it can be time and money consuming to make modifications to the system. At worst, modifying the insufficient AS/RS may cause waiting for the supplier or consumer filling or emptying the warehouse. Financial results can be extensive.

The third most significant financial benefit is the support for defining and filling a capacity guarantee for AS/RS. With simulation, it is possible to test that the designed system actually fills the capacity guarantee. Without simulation, assumptions about the system capacity are only rough. Therefore, it is possible that the system will not fill the promised capacity values in the test runs with the real AS/RS. That will probably affect the total purchase price notably.

7.2 Future work

This subsection introduces future research proposals for the AS/RS simulation studies. This work focused only on three quite specific research questions, and therefore, several potential future research proposals were identified.

The first proposal for future research concerns the device utilization ratios. In this work, only utilization ratios of the industrial robots and stacker cranes were assessed. However, there are also other devices to be analyzed. For example, utilization ratios of packing stations could be interesting especially if the operators at the packing stations were modeled more accurately. Also the utilization ratio of the conveyor system would be interesting. However, there are several conveyors in the system. For this reason, the utilization ratio should be somehow generalized to present the utilization ratio of the whole conveyor system.

The second proposal for future research deals with the storage strategy. In this work the utilized storage strategy is random storage. In the future it would be interesting to see that how the system would work if different storage strategies were utilized. Probably this would have an effect on the stacker crane utilization ratios. Especially, in the system where the stacker crane utilization ratio would be higher the analysis of utilizing different storage strategies would be interesting.

Thirdly, it would be interesting and worthwhile to make sensitivity analysis so that all of the uncertain parameters were varied in same simulation setup. The benefit would be that also the combined effect of the uncertain parameters was analyzed. Presenting and analyzing the results could be a bit more challenging compared to setup where one parameter at time is varied.

The fourth proposal for future research is simulation of the AS/RS with more realistic production and order data. It would be the best alternative to simulate the system with real production and order data provided by the AS/RS customer. This would lead to the most realistic results. The data could be utilized as raw data or as distributions generated from the data. For example in reference [37], data analysis and distribution generation is presented in more details.

The fifth proposal for future research is virtual commissioning for the AS/RS. This means that the WMS of the simulation platform would be replaced with the WMS that will be also utilized in the real system. This enables more realistic simulation results because there can be differences between the simulation platform WMS and the real WMS. Besides the more realistic results, also the real WMS would be tested and validated before the actual commissioning. This would save time and money during the actual commissioning.

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APPENDIX A

Device utilization ratios (%) of material flow simulations as data tables.

Stacker crane

Infeed / Outfeed	624	1056	1440	1872	2304
1344	30.84	37.51	43.62	50.43	54.93
1824	38.46	44.67	52.26	58.15	63.71
2304	47.34	51.89	59.24	63.13	70.39
2880	56.45	61.13	67.67	70.61	75.52
3360	63.28	68.69	71.25	74.08	75.52

Industrial robot

Infeed / Outfeed	624	1056	1440	1872	2304
1344	35.18	43.52	49.52	59.27	66.73
1824	43.24	51.32	59.29	67.14	75.10
2304	51.95	59.93	67.42	75.25	83.46
2880	61.93	69.98	78.00	84.66	92.01
3360	71.29	78.12	84.82	92.22	97.01